

CRANFIELD UNIVERSITY

Ai Sugiura

WATERRENEW: WASTEWATER POLISHING USING

RENEWABLE ENERGY CROPS.

SCHOOL OF APPLIED SCIENCES

PhD THESIS
Academic year: 2005-08

Supervisor: Dr Sean F. Tyrrel
February 2009

CRANFIELD UNIVERSITY

SCHOOL OF APPLIED SCIENCES

PhD THESIS

Academic Year 2005-2008

A. SUGIURA

WaterRenew: wastewater polishing using renewable energy crops.

Supervisor: Dr Sean F. Tyrrel

February 2009

This thesis is submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

© Cranfield University 2009. All rights reserved. No part of this publication may be reproduced without the written permission of the copyright owner.

ABSTRACT

The research described in this thesis is part of a wider EU-LIFE project, the WaterRenew project. The WaterRenew concept can be described as the recovery of nutrients from wastewater which can lead to eutrophication of surface waters, by irrigation of short rotation coppice in order to fertilise them. Such systems have been proven to function properly as nutrient removal systems when studied for N removal and have already been successfully and commercially implemented in different countries. However, the factors potentially preventing them from operating sustainably have not been identified nor their upper limits quantified with confidence. A WaterRenew system can indeed be looked at as a unit composed with three main compartments; soil, soil water and plant. Therefore, the sustainability of such a system will be compromised if at least one of these compartments is changed irreversibly. The limits can be hydrological with constant runoff or drainage being induced. They can also be chemical with inadequate amounts of nutrients removed from the effluent applied or irreversible accumulation of nutrients in soil. Finally, these limits can be physiological with the trees' health being irreversibly compromised. Moreover, the relevance and effectiveness of such a system under UK conditions has not been established yet.

In this context, a field trial was set up at Cranfield University sewage treatment works where the secondary treated effluent was irrigated on to *Salix viminalis*, *Populus trichocarpa* and *Eucalyptus gunnii* trees planted at a density of 13,060 trees.ha⁻¹, on a chalky clayey soil, in order to maintain soil water content at field capacity. To tackle more specifically P fate processes understanding, an independent P leaching soil column experiment was also set up.

With the latter settings, it was possible to apply high volumes of effluent (3625 mm for willow, 2895 mm for poplar and 3345 mm for eucalyptus for the 2 years of irrigation) and high amounts of nutrients (1023 kg-N.ha⁻¹ and 134 kg-P.ha⁻¹ for willow, 834 kg-N.ha⁻¹ and 108 kg-P.ha⁻¹ for poplar and 946 kg-N.ha⁻¹ and 127 kg-P.ha⁻¹ for eucalyptus for the 2 years of irrigation).

It was found that irrigation with effluent increased significantly tree yields so that they were within the range reported in the literature for willow and eucalyptus but slightly lower for poplar. The trees uptook between 20 % and 50 % of the total amounts of N and P applied with eucalyptus uptaking more nutrients than willow, which in turn took up more than poplar. Then, it was found that irrigation did not have any significant

effect on N and P in soil and the amounts applied remained very low compared to the existing nutrients soil pools. However, irrigation did have a significant effect on increasing K and Na in soil. Na increased enough to induce a significant increase in soil SAR but soil remained neither saline nor alkali. The trees had a smaller impact on soil chemistry. Finally, it was found also that irrigation did not have any significant effect on N and P in soil water with no P detectable in any of the soil water and groundwater samples during the whole experiment. Irrigation did, however, increase significantly K and Na concentrations in soil water and for K also in groundwater. From the point of view of nutrients removal, although a tree effect was measurable, it was not as important as the functions of the soil. Thus, when a WaterRenew system is maintained under a hydrological constraint, with the soil moisture kept at field capacity, it was still possible to apply high volumes of effluent, even on a clayey soil. In addition, the consequent high amounts of nutrients applied were efficiently retained between tree uptakes and mainly soil organic and inorganic nutrients' pools. Indeed, the amounts of nutrients lost by drainage remained low (<10 % of the total amounts applied) for N and P and groundwater was efficiently protected from pollution on this site.

On P dynamic processes understanding, it was found that P leaching patterns depend highly on soil moisture and to a lesser extent on the amount of P applied. When soil is saturated, P will start leaching even when applied at a very low concentration.

A model, the WR_MODEL, was developed which integrates the observations, measurements and understanding of Cranfield University sewage treatment work field trial and soil column experiment into a model. The purpose of WR_model is to help the design and implementation of a WaterRenew system in any location as long as climatic and soil data are available. The model default values are for England and Wales climatic and soil data.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor Dr. Sean F. Tyrrel and field technician Ian Seymour for their continuous support, encouragement, advice and assistance throughout this PhD.

Thanks are also due to the staff at the soil- water laboratory at Cranfield University, in particular to Richard Andrews, Maria Bikupska, Jan Bingham and Susan Welch for their help, flexibility and patience during the very very long laboratory analysis. A special thank to the precious tea breaks at the laboratory and encouragement; real energy boost!

I also wish to gratefully acknowledge the WRc team, in particular Dr. Barbara Hudec in charge with the WaterRenew project, the project partners from AfBI, Dr. Alistair Mc Cracken and Dr. Astrid Werner and also Dr. Drusilla Riddell-Black from Lupus Science.

And finally, I would like to give a special thank you to each new friend I have been lucky enough to meet during my time at Cranfield University as well as passing on those thanks to my other friends around the world, of whom I have also been lucky enough to know.

TABLE OF CONTENT

Abstract	i
Acknowledgements	iii
Table of content	iv
List of figures	xii
List of tables	xviii
Notation	xxiii
Chapter 1: Introduction	
1. RESEARCH BACKGROUND.....	1-1
2. RESEARCH AIM.....	1-2
3. THESIS OUTLINE AND METHODOLOGY	1-2
4. REFERENCES.....	1-4
 Chapter 2: Wastewater fertigation in renewable energy production: a review of risks and benefits	
1. INTRODUCTION	2-1
1.1 WHY IS WASTEWATER TREATED?	2-1
1.2 WHAT IS THE FUTURE OF RENEWABLE ENERGY CROPS IN THE UK?	2-4
1.3 WHICH WASTEWATER OR WASTEWATERS?	2-5
1.4 FEASIBILITY AND SUSTAINABILITY OF FERTIGATION OF ENERGY CROPS WITH DOMESTIC SEWAGE ?	2-7
2. NUTRIENTS FATE IN WASTEWATER IRRIGATION OF ENERGY CROPS: WHERE ARE THE RISKS?.	2-8
2.1 TREE RESPONSE TO NUTRIENTS	2-8
2.1.1 Willow, Poplar and Eucalyptus in the UK: water use, yield and cultural practices	2-8
2.1.2 SRC of Willow, Poplar and Eucalyptus: nutrients fate.....	2-10
2.2 SOIL ROLE IN NUTRIENTS REMOVAL	2-12
2.2.1 Soil capacity to retain and transform nutrients	2-12
2.2.2 Conceptual model of soil “treatment” capacity.....	2-13
2.2.3 Soil processes and susceptibility to environmental risks	2-15
2.3 CONCLUSION	2-23
3. RISKS OF WASTEWATER IRRIGATION FOR CROP PRODUCTION TO SUSTAINABILITY: NON NUTRIENTS ASPECTS	2-24
3.1 TREE STRESS MANAGEMENT CAPACITY	2-24
3.2 PUBLIC HEALTH RISKS BECAUSE OF PRESENCE OF PATHOGENS IN WASTEWATER	2-25
3.3 RISK OF ACCUMULATION OF HEAVY METAL OR HAZARDOUS MATERIAL THAT WILL BE STORED IN THE TREES AND RELEASED WHEN BURN OR ACCUMULATION OF HEAVY METALS IN SOIL.....	2-28
3.3.1 Heavy metals in wastewater and risk of accumulation of heavy metals in soil	2-28
3.3.2 Accumulation of heavy metals in plants and effect on yields.....	2-29

3.4	RISK OF INCREASED ATMOSPHERIC EMISSION OF GREENHOUSE EFFECT GAS BY DENITRIFICATION OF WASTE NITRATE APPLIED ON SOIL	2-31
3.5	RISK OF SOIL SALINISATION	2-32
3.6	RISK ON RIVER AND GENERAL HYDROLOGY	2-32
4.	CONCLUSION	2-33
5.	RESEARCH AIM AND OBJECTIVES	2-35
6.	REFERENCES.....	2-36

Chapter 3: Field trial – Materials and methods

1.	INTRODUCTION	3-1
1.1	CRANFIELD FIELD TRIAL CONTEXT- SPECIFIC OBJECTIVE	3-1
1.2	OVERVIEW	3-2
2.	SITE CHARACTERISTICS.....	3-2
2.1	LOCATION AND SITE HISTORY	3-2
2.2	CRANFIELD WEATHER	3-4
2.3	SOIL CLASSIFICATION IN CRANFIELD AND EVALUATION FOR IRRIGATION	3-7
2.3.1	Nitrogen content in soil	3-8
2.3.2	Available phosphorus in soil	3-9
2.3.3	Exchangeable, available potassium content.....	3-10
2.4	CHARACTERISTICS OF THE EFFLUENT IN THE TREATMENT WORK	3-11
3.	TRIAL DESCRIPTION	3-13
3.1	EXPERIMENTAL DESIGN	3-13
3.2	PLOT LAYOUT	3-14
3.3	PLOT CONSTRUCTION	3-15
4.	TREE SPECIES CHOICE.....	3-16
4.1	TREE SELECTION.....	3-16
4.2	PLANTING	3-17
5.	IRRIGATION SYSTEM DESIGN AND SETTINGS.....	3-18
5.1	WATERING PHILOSOPHY	3-18
5.2	HOW TO DETERMINE FIELD CAPACITY	3-19
5.3	IRRIGATION SYSTEM SETTINGS (MATERIAL).....	3-21
6.	DATA COLLECTION-MONITORING SYSTEM	3-22
6.1	SOIL MONITORING, SAMPLING AND ANALYSES	3-22
6.2	SOIL WATER MONITORING, SAMPLING AND ANALYSES	3-25
6.2.1	Soil water sampling settings	3-25
6.2.2	Sampling frequency in space and in time	3-28
6.2.3	Material and methods for soil water and groundwater sampling	3-28
6.2.4	Methods for groundwater sampling.....	3-29
6.2.5	Chemical analyses on soil water and groundwater.....	3-29
6.3	PLANT MONITORING, SAMPLING AND ANALYSES.....	3-31
6.3.1	Plant growth monitoring	3-31
6.3.2	Wood and leaf sampling methods.....	3-31
6.3.3	Wood and leaf material nutrient analysis.....	3-31
6.4	HYDROLOGICAL MEASUREMENTS.....	3-32
6.4.1	THETA PROBE on each plot.....	3-32

6.4.2	DIVINER reading on 170 cm profile on each plot	3-33
7.	STATISTICAL ANALYSIS MODEL.....	3-34
7.1	GENERAL LINEAR MODEL, FACTORS DESCRIPTION	3-34
7.1.1	Soil water composition and soil chemical composition.....	3-34
7.1.2	Groundwater analysis.....	3-36
7.1.3	Tree growth	3-36
7.2	GENERAL STEPS TO STATISTICAL ANALYSES	3-37
8.	CONCLUSION	3-38
9.	REFERENCES.....	3-39

Chapter 4: Growth and water use of *Salix viminalis*, *Populus trichobel* and *Eucalyptus gunnii* field trial plantation irrigated with secondary treated effluent

1.	INTRODUCTION	4-1
2.	METHODS.....	4-2
2.1	SITE AND STAND DESCRIPTION.....	4-2
2.2	EXPERIMENTAL DESIGN AND TREATMENTS, FIELD WORK	4-3
2.3	GROWTH MEASUREMENTS.....	4-4
2.4	WATER-USE ESTIMATES	4-5
2.5	CROP FACTOR	4-9
2.6	FOLIAR AND WOOD NUTRIENTS.....	4-10
2.7	STATISTICAL ANALYSIS	4-11
2.8	WATER AND NUTRIENT USE EFFICIENCIES	4-11
2.8.1	Water use efficiency.....	4-11
2.8.2	Nutrient use efficiency	4-12
3.	RESULTS AND DISCUSSION	4-12
3.1	CLIMATE	4-12
3.2	STAND GROWTH	4-15
3.2.1	Stem length	4-15
3.2.2	Foliar and woody biomass	4-17
3.2.3	Leaf Area Index	4-27
3.3	WATER USE.....	4-30
3.3.1	Irrigated volumes per trees.....	4-30
3.3.2	Water use efficiency.....	4-33
3.3.3	Crop factors.....	4-34
3.4	AVERAGE ANNUAL REMOVAL OF NUTRIENTS AND NUTRIENT USE EFFICIENCY	4-38
3.4.1	Nutrient concentration in leaf and wood.....	4-38
3.4.2	Nutrient uptake, nutrient use efficiency in wood and leaf.....	4-43
3.4.3	Nutrient use efficiency	4-50
4.	CONCLUSIONS.....	4-51
5.	REFERENCES.....	4-54

Chapter 5: Changes in soil chemistry in effluent irrigated willow, poplar, eucalyptus planted field trial

1. INTRODUCTION	5-2
2. MATERIAL AND METHODS	5-3
2.1 SITE	5-3
2.2 TREATMENTS.....	5-4
2.3 EFFLUENT	5-5
2.4 CHEMICAL ANALYSIS OF IRRIGATION WATER	5-6
2.5 SOIL SURVEY	5-6
2.6 SOIL CHEMICAL ANALYSIS	5-6
2.7 STATISTICAL ANALYSIS	5-7
3. RESULTS AND DISCUSSION	5-7
3.1 IRRIGATION WATER AND AMOUNT OF NUTRIENTS APPLIED BY IRRIGATION	5-7
3.1.1 Nitrogen application.....	5-8
3.1.2 Phosphorus application.....	5-10
3.1.3 Potassium application	5-12
3.1.4 Nutrients application	5-13
3.2 SALINITY	5-14
3.2.1 Effluent pH, EC and Na concentration.....	5-14
3.2.2 Sodium Adsorption Ratio (SAR, qualitative) in irrigation effluent.....	5-17
3.3 SOIL PH	5-18
3.4 SOIL SAR, SODIUM, CALCIUM+MAGNESIUM IN SATURATED PASTE EXTRACT	5-21
3.5 ESP AND EC.....	5-25
3.6 SOIL Na EXTRACTED IN AMMONIUM NITRATE OR EXTRACTABLE Na.....	5-27
3.7 SOIL ORGANIC MATTER CONTENT	5-35
3.8 NITROGEN EVOLUTION IN SOIL	5-38
3.8.1 Total Oxidised Nitrogen and Ammonium	5-38
3.8.2 Total Nitrogen (TN, g.kg ⁻¹ of soil)	5-44
3.9 PHOSPHORUS EVOLUTION IN SOIL (TOTAL AND OLSEN)	5-48
3.9.1 Olsen-P or plant available P.....	5-48
3.9.2 Total Phosphorus (TP, g.kg ⁻¹ of soil).....	5-54
3.10 POTASSIUM EVOLUTION IN SOIL (TOTAL AND AVAILABLE)	5-60
3.10.1 Available Potassium	5-60
3.10.2 Total Potassium	5-66
4. CONCLUSION	5-67
5. REFERENCES.....	5-68

Chapter 6: Evolution of soil water and groundwater chemistry on planted plots irrigated with secondary treated effluent

1. INTRODUCTION	6-1
2. MATERIAL AND METHODS	6-3
2.1 SITE	6-3
2.2 TREATMENTS.....	6-3
2.3 SAMPLING OF IRRIGATION WATER, SOIL WATER AND GROUNDWATER	6-4
2.4 CHEMICAL ANALYSIS OF IRRIGATION WATER	6-5
2.5 STATISTICAL ANALYSIS	6-5
3. RESULTS AND DISCUSSION	6-6
3.1 COMPOSITION OF THE EFFLUENT USED FOR IRRIGATION	6-6

TABLE OF CONTENT

3.2	PHOSPHATE AND TOTAL PHOSPHATE	6-7
3.2.1	<i>Phosphate and total phosphate in soil water</i>	6-7
3.2.2	<i>Phosphate and total phosphate in groundwater</i>	6-8
3.3	NITROGEN IN SOIL WATER AND GROUNDWATER	6-11
3.3.1	<i>Ammonia in soil water</i>	6-11
3.3.2	<i>TON in soil water</i>	6-13
3.3.3	<i>TN in soil water</i>	6-17
3.3.4	<i>Nitrogen in groundwater</i>	6-20
3.4	POTASSIUM IN SOIL WATER AND GROUNDWATER	6-24
3.4.1	<i>K in soil water</i>	6-24
3.4.2	<i>K in groundwater</i>	6-27
3.5	SODIUM IN SOIL WATER AND IN GROUNDWATER	6-29
3.5.1	<i>Na in soil water</i>	6-29
3.5.2	<i>Na in groundwater</i>	6-33
3.6	PH AND EC IN SOIL WATER AND GROUNDWATER.....	6-35
3.6.1	<i>pH and EC in soil water</i>	6-35
3.6.2	<i>pH and EC in soil water</i>	6-39
4.	CONCLUSION	6-40
5.	REFERENCES.....	6-42

Chapter 7: Nutrient balances in a WaterRenew system

1.	INTRODUCTION	7-2
2.	MATERIALS AND METHODS	7-5
2.1	SITE	7-5
2.2	TREATMENTS.....	7-5
2.3	SOIL MOISTURE MEASUREMENTS	7-6
2.3.1	<i>Theta probes (SM200, Delta-T)</i>	7-6
2.3.2	<i>DIVINER (DIVINER 2000, Sentek sensor technology)</i>	7-6
3.	DRAINAGE ASSESSEMENT.....	7-7
3.1	CRUDE ASSESSMENT OF DRAINAGE WITH RAINFALL DATA ONLY	7-8
3.1.1	<i>Assessment of the drained volume of soil water</i>	7-8
3.1.2	<i>Assessment of the leached amounts of nutrients</i>	7-9
3.2	ASSESSMENT OF DRAINAGE BY THETA PROBE SOIL MOISTURE READING AVERAGED DAILY	7-11
3.2.1	<i>Assessment of the drained volume of soil water</i>	7-11
3.2.2	<i>Assessment of the leached amount of nutrients by drainage</i>	7-14
3.3	ASSESSMENT OF DRAINAGE BY DIVINER DATA AND MET DATA.....	7-15
3.3.1	<i>Assessment of the drained volume of soil water</i>	7-15
3.3.2	<i>Assessment of amounts of nutrients leached</i>	7-19
3.4	COMPARISON OF THE AMOUNT OF NUTRIENTS LEACHED UNDER THE DIFFERENT COVERS ACCORDING TO THE DIFFERENT CALCULATIONS OF DRAINAGE	7-19
4.	TOTAL BALANCE USING DRAINAGE CALCULATED WITH DIVINER DATA.....	7-20
4.1	TOTAL NITROGEN BALANCE AND N FATE	7-22
4.2	TOTAL PHOSPHORUS BALANCE AND P FATE.....	7-27
4.3	TOTAL POTASSIUM BALANCE AND K FATE.....	7-31
4.4	NA BALANCE	7-34
5.	CONCLUSION	7-36
6.	REFERENCES.....	7-39

Chapter 8: Phosphorus leaching as affected by wastewater application and soil moisture levels

1. INTRODUCTION	8-2
2. MAXIMUM P SORPTION CAPACITY: DEFINITION AND DETERMINATION METHOD.....	8-4
2.1.1 Olsen-P threshold.....	8-4
2.1.2 Freundlich equation from phosphorus sorption isotherm	8-5
3. MATERIAL AND METHODS	8-6
3.1 INITIAL SOIL PHOSPHORUS CHARACTERISATION	8-6
3.1.1 Olsen-P determination.....	8-6
3.1.2 Phosphorus sorption Isotherm determination	8-7
3.2 SOIL COLUMNS.....	8-7
3.2.1 Preparation of columns	8-7
3.2.2 Phosphorus leaching experiment: hypothesis and four treatments	8-8
3.2.3 Flow uniformity check with bromide spiking.....	8-9
3.2.4 Leachate and soil analysis.....	8-10
3.3 DATA ANALYSIS	8-11
4. RESULTS AND DISCUSSION	8-13
4.1 INITIAL SOIL PHOSPHORUS CHARACTERISATION	8-13
4.1.1 Initial Olsen-P	8-13
4.1.2 Phosphorus sorption Isotherm and Freundlich equation	8-13
4.2 PHOSPHORUS LEACHING BEHAVIOUR	8-15
4.2.1 Bromide spiking results	8-15
4.2.2 pH measurements in leachate.....	8-19
4.2.3 Phosphorus leaching pattern.....	8-20
4.3 PHOSPHORUS DISTRIBUTION IN SOIL COLUMNS	8-31
4.3.1 Olsen-P distribution in soil column.....	8-31
4.3.2 Total phosphorus (TP) in soil column	8-33
4.3.3 Relationship between P applied and Olsen-P build up in soil	8-35
5. CONCLUSION	8-36
6. REFERENCES.....	8-39

Chapter 9: Modelling framework: WaterRenew system design and decision support tool

1. INTRODUCTION	9-1
2. CONCEPTUALISATION.....	9-4
2.1 MODEL DEFINITION	9-4
2.2 MAIN PRINCIPLES	9-4
3. MODEL DESCRIPTION.....	9-9
3.1 SOIL WATER BALANCE IN WR_MODEL	9-9
3.2 INPUTS, OUTPUTS AND OPERATIONS TAKEN IN ACCOUNT IN WR_MODEL	9-10
3.2.1 Model assumption.....	9-10
3.2.2 Model processes, inputs and outputs	9-10
3.3 THE TECHNICAL SUB-MODEL	9-12
3.3.1 Model step by step description	9-12
3.3.2 Model assumptions	9-19
3.4 COST BENEFIT ANALYSIS	9-21
3.4.1 Costs considered.....	9-21

TABLE OF CONTENT

3.4.2	<i>Benefit considered</i>	9-23
3.4.3	<i>Financial balance, net income</i>	9-24
3.5	SCENARIOS COMPARED BY DEFAULT	9-25
4.	VERIFICATION AND SENSITIVITY ANALYSIS	9-26
4.1	VERIFICATION	9-26
4.2	SENSITIVITY ANALYSIS	9-28
4.2.1	<i>Definition and selection of parameters and variables</i>	9-28
4.2.2	<i>Results on example data set (Godinton) on the sensitivity analysis</i>	9-29
5.	CONCLUSION	9-31
6.	REFERENCES	9-31
7.	APPENDICES	9-33
7.1	APPENDICE 1: MAP OF ENGLAND AND WALES CLIMATIC ZONES	9-33
7.2	APPENDICE 2: WR_MODEL USERGUIDE: WATERRENEW MODEL USER GUIDE	9-34

Chapter 10: Conclusions and recommendations

1.	GENERAL CONCLUSIONS	10-1
2.	CRITICAL ASSESSMENT OF ACHIEVEMENT	10-8
3.	RECOMMENDATIONS FOR FUTURE RESEARCH	10-10

LIST OF FIGURES

Chapter 1: Introduction

Figure 1 Thesis outline with nutrients (N, P, K, and Na) fate and interactions between the different compartments of a WaterRenew system (soil, soil water, plant). 1-4

Chapter 2: Wastewater fertigation in renewable energy production: a review of risks and benefits

Figure 1 Evolution of nutrients status in England and Wales' rivers. Rivers with nutrients' content classified as "high or above", i.e. with a phosphate concentration greater than 0.1 mg.L⁻¹ and nitrate concentrations greater than 30 mg.L⁻¹. (Source: Environment Agency, 2008) 2-3

Figure 2 Conceptual model summarising nutrients processes occurring in the soil-water-plant system 2-13

Figure 3 A generalised scheme of phosphorus dynamics in a WaterRenew system. 2-20

Figure 4 Origin and fate of metals during treatment of wastewater, from ADEME 1995, source: ICON, 2001 2-29

Chapter 3: Field trial – Materials and methods

Figure 1 Monthly average rainfall (mm/month) and ET₀ (FAO Penman-Monteith reference evapotranspiration calculated with CROPWAT) at Bedford (20km from Cranfield), Bedfordshire from 1967 to 2007. Source: Silsoe automated Met Office. (Vertical bars denote standard deviation)..... 3-4

Figure 2 Monthly rainfall (mm) at Silsoe for 2006, 2007 and the monthly average for 1962-2007. Source: Silsoe met station and Met Office. (Vertical bars denote standard deviation) 3-5

Figure 3 Monthly ET₀ (FAO Penman-Monteith reference evapotranspiration calculated with CROPWAT, mm) at Silsoe for 2006, 2007 and the monthly average for 1962-2007. Source: Silsoe met station and Met Office. (Vertical bars denote standard deviation) 3-5

Figure 4 Mean monthly maximum, minimum and mean daily air temperature at Bedford (20km from Cranfield), Bedfordshire from 1971 to 2000. Source: Met Office..... 3-6

Figure 5 Mean Total Soil Nitrogen content (%) by depth in February 2006 at 6 depths from 10 cm-170 cm collected in February 2006 (n=8). According to FAO 55, if total soil N was less than (--) 0.1% , it was probable to observe a fertiliser application response, and if total soil N was greater than (--) 0.3%, it was unlikely to observe a fertiliser application response..... 3-8

Figure 6 Average extractable P concentrations in soil (Olsen P) in mgP.L⁻¹ of Cranfield soil at 6depths from 10 cm to 170 cm collected in February 2006 (n=8). According to FAO 55, Olsen-P less than (left --) 5mg.L⁻¹, it was probable to observe a fertiliser application response, and if Olsen-P greater than (right --) 11mg.L⁻¹, it was unlikely to observe a fertiliser application response. RB 209 indexes are also reported (MAFF 2000). 3-9

Figure 7 Average extractable K content in kgK.ha⁻¹ of Cranfield soil at 6depths from 10 cm to 170 cm collected in February 2006 (n=8). According to FAO 55, if available K was less than (--) 100kgK.ha⁻¹, it was probable to observe a fertiliser application response, and if available K was greater than (--) 300kgK.ha⁻¹, it was unlikely to observe a fertiliser application response. 3-10

Figure 8 Average extractable K content in mg-K.L⁻¹ of Cranfield soil at 6 depths from 10 cm to 170 cm collected in February 2006 (n=8). According to RB209, index-K 2, target index, corresponds to values between 121 and 241 mg-K.L⁻¹ (--)..... 3-11

Figure 9 Sewage treatment processes on Cranfield sewage treatment works, from raw effluent arrival point, 1) the effluent goes to a sedimentation tank where primary treatment takes place with sedimentation of solids contained in the effluent. 2) The primary treated effluent is sprayed on percolating filters where the biological step takes place. 3) The secondary treated effluent is then delivered in a humus tank where solids are removed. 4) This solid removed secondary treated effluent is re-pumped into a last percolating filter tank. 5) Ammonium content of this last effluent doesn't fulfil the discharge consent limits ($>6 \text{ mg.L}^{-1}$ of NH_4), hence it was sprayed on nitrifying filters where nitrification takes place. 6) The nitrified secondary treated effluent was sent to a final clarifier, radial flow humus tank, where a final solids removal takes place. 7) this final effluent is discharged in the river Chicheley Brook.	3-12
Figure 10 Experimental design.....	3-14
Figure 11 Cranfield site field trial map, localisation of 24 randomly distributed plots, 3 replicates of 4 covers, unplanted, eucalyptus, willow and poplar, irrigated or not.	3-15
Figure 12 Water release curve for the first 10 cm of soil on 8 plots. (→) Field capacity range... 3-20	3-20
Figure 13 Irrigation system layout.....	3-21
Figure 14 Model of the sub-soil organization once the crop will be established (Oz dimension) 3-27	3-27
Figure 15 Air view of the middle of the plot (4 inner trees) and localization of the suction cup samplers.....	3-28
Figure 16 Localisation of the DIVINER hole on each plot	3-33
Figure 17 Thesis outline with nutrients (N, P, K, and Na) fate and interactions between the different compartments of a WaterRenew system (soil, soil water, plant).	3-39
Chapter 4: Growth and water use of and field trial plantation irrigated with secondary treated effluent	
Figure 1 Cranfield site field trial map, localisation of 24 randomly distributed plots, three replicates of four covers, unplanted, eucalyptus, willow and poplar, irrigated or not.	4-3
Figure 2 Mean monthly rainfall in mm (bars) and FAO Penman-Monteith reference evapotranspiration (---) in mm over 30 years (1975-2005) and in 2005, 2006, and 2007.. 4-13	4-13
Figure 3 Potential soil moisture deficit (mm) (PSMD), average over 30 years (1975-2005), in 2005, 2006 and 2007.	4-14
Figure 4 Evolution of stem height (m) from July 2006 until February 2008 of <i>S. viminalis</i> , <i>P. trichocarpa</i> and <i>E. gunnii</i> stands irrigated with secondary treated effluent or not irrigated for 32 months. (Dashed zones indicate the period of irrigation and vertical bars denote 0.95 confidence interval.)	4-16
Figure 5 Evolution of wood biomass (odt.ha^{-1}) from July 2006 until February 2008. (Dashed zones represents the periods when irrigation was on). Month 0 was March 2006. Vertical bars denote standard deviations.	4-20
Figure 6 Evolution of cumulative foliar biomass (odt.ha^{-1}) from July 2006 until February 2008. (Dashed zones represents the periods when irrigation was on. Month 0 was March 2006 and month 22, February 2008. Vertical bars denote standard deviations).....	4-26
Figure 7 Evolution of LAI from July 2006 until February 2008. (Dashed zones represents the periods when irrigation was on. Month 0 was March 2006.)	4-29
Figure 8 Irrigated volume on <i>E.gunnii</i> , <i>P. Trichocarpa</i> , <i>S.viminalis</i> and unplanted plots and PSMD from July 2006 until January 2008.	4-30

Figure 9 Effluent use efficiency for woody biomass production and corresponding linear regression on averaged data for willow, poplar and eucalyptus from July 2006 until January 2008.....	4-33
Figure 10 Evolution of K_c for irrigated willow trees, calculated and modelled (---) and LAI.	4-36
Figure 11 Evolution of K_c for irrigated poplar trees, calculated and modelled (---) and LAI. ...	4-36
Figure 12 Evolution of K_c for eucalyptus trees, calculated and modelled (---) and LAI. As eucalyptus trees do not lose their leaves during winter, it was considered Etc would not be lower than grass, hence ET_0 , there fore K_c was equalled to 1.	4-37

Chapter 5: Changes in soil chemistry in effluent irrigated willow, poplar, eucalyptus planted field trial

Figure 1 Cranfield site field trial map, localisation of 24 randomly distributed plots, 3 replicates of 4 covers, unplanted, eucalyptus, willow and poplar, irrigated or not.	5-4
Figure 2 Nitrogen applied by irrigation during each of the two irrigation season (July 2006-February 2007 and March 2007-February 2008) on each of the 4 covers (Eucalyptus, Poplar, Unplanted and Willow).	5-9
Figure 3 Phosphorus applied by irrigation during each of the two irrigation season (July 2006-February 2007 and March 2007-February 2008) on each of the 4covers (Eucalyptus, Poplar, Unplanted and Willow).	5-11
Figure 4 Potassium applied by irrigation during each of the two irrigation season (July 2006-February 2007 and March 2007-February 2008) on each of the 4covers (Eucalyptus, Poplar, Unplanted and Willow). 50 kg.ha ⁻¹ of K recommended by RB 209.....	5-13
Figure 5 Sodium applied by irrigation during each of the two irrigation season (July 2006-February 2007 and March 2007-February 2008) on each of the 4 covers (Eucalyptus, Poplar, Unplanted and Willow).	5-16
Figure 6 Average pH per year. Vertical bars denote 0.95 confidence interval. Soil pH above 7 are considered alkaline (Rowell, 1994).	5-18
Figure 7 Effect of cover type and irrigation on pH data presented for averages of 3 depths. Vertical bars denote standard deviation.	5-19
Figure 9 Mean SAR regrouped by irrigation or not. Vertical bars denote standard deviation..	5-24
Figure 10 Soil classification according to EC and ESP. (Richards, 1954).....	5-25
Figure 11 Average extractable Na concentration in soil grouped by covers from samples collected at 3 depth (10 cm, 30 cm, 50 cm) and 3years (2006, 2007, 2008).	5-28
Figure 12 Linear regression on variation in extractable Na in soil (kg/ha) at 10, 30 and 50 cm in relation with the Na amount applied (kg/ha). Straight vertical line represents the amount of Na applied in 2006 and dotted vertical line represents the amount of Na applied in 2007.	5-31
Figure 13 Evolution of extractable Na concentration in soil samples collected at 3 depths (10 cm, 30 cm and 50 cm) under 4 covers (unplanted, willow, eucalyptus, poplar) from irrigated plots. Horizontal bars denote 0.95 confidence interval. The graph is drawn staggered at each depth for clarity.	5-32
Figure 14 Extractable Na concentration in soil grouped by year and irrigation. Vertical bars denote 0.95 confidence interval.	5-33
Figure 15 Mean soil organic matter (%) distribution in soil grouped by depth (horizontal bars denotes 0.95 confidence interval).	5-35

Figure 16 Mean soil organic matter (%) in soil at 3 depths (10, 30 and 50 cm), under 4 covers (unplanted, eucalyptus, poplar and willow) from irrigated or not plots over 3 years (2006, 2007, 2008). The graph is drawn staggered at each depth for clarity.....	5-37
Figure 17 TON and ammonium grouped by irrigation or not (vertical bars denote 0.95 confidence interval).	5-38
Figure 18 Mineral Nitrogen evolution in soil (total, TON and ammonium) grouped by year (vertical bars denotes standard deviation).	5-40
Figure 19 Mean TON regrouped by year and irrigation. Vertical bars denote 0.95 confidence interval calculated with yearly standard deviation.....	5-41
Figure 20 Comparison of TON measurements from the selected plots with vertical bars to denote 0.95 confidence interval calculated from standard deviation of all the measurements on a year.	5-42
Figure 21 Mean Ammonium regrouped by year and irrigation. Vertical bars denote 0.95 confidence interval calculated with yearly standard deviation.	5-43
Figure 22 TN distribution under the 4 different covers (willow, poplar, eucalyptus, and unplanted) irrigated or not, grouped by depth (10 cm, 30 cm and 50 cm). The graph is drawn staggered at each depth for clarity	5-45
Figure 23 TN evolution grouped by year and irrigation or not. (\pm standard deviation).....	5-46
Figure 24 Mean Olsen's P concentration on the average between irrigated and non-irrigated plots covered with willow, poplar, eucalyptus and unplanted (horizontal bars denote standard deviation).	5-49
Figure 25 Evolution of Olsen-P in soil (from 0-60 cm depth) averaged by year, irrigation and covers.	5-50
Figure 26 Olsen-P evolution in soil at 3 depths (10, 30 and 50 cm), under 4 covers (unplanted, eucalyptus, poplar and willow) irrigated from February 2006, 2007 and 2008. Vertical line (–) represents 60mgP/kg of soil identified as change point concentration before Phosphorus can be detected in drainage water (Mamo et al., 2005; McGechan and Lewis, 2002/5; McGechan, 2002/6).	5-52
Figure 27 Olsen-P evolution in soil at 3 depths (10, 30 and 50 cm), under 4 covers (unplanted, eucalyptus, poplar and willow) non irrigated from February 2006, 2007 and 2008. Vertical line (→) represents 60mgP/kg of soil identified as change point concentration before Phosphorus can be detected in drainage water (Brookes et al., 1997).	5-53
Figure 28 Evolution of average TP concentration under all covers from 2006 to 2008, under irrigation with secondary treated effluent or not.	5-56
Figure 29 Total-P evolution in soil at 3 depths (10, 30 and 50 cm), under 4 covers (unplanted, eucalyptus, poplar and willow) irrigated from February 2006, 2007 and 2008. The graph is drawn staggered at each depth for clarity.	5-58
Figure 30 Total-P evolution in soil at 3 depths (10, 30 and 50cm), under 4 covers (unplanted, eucalyptus, poplar and willow) non irrigated from February 2006, 2007 and 2008. The graph is drawn staggered at each depth for clarity.	5-59
Figure 31 plot of mean available K grouped by cover for all depth, year and irrigated or not. Vertical bars denote 0.95 confidence interval.	5-61
Figure 32 Mean plot of available K (mg.kg^{-1} of soil) grouped by year. Vertical bars denote 0.95 confidence interval.	5-63
Figure 33 Available Potassium evolution in soil at 3 depths (10, 30 and 50cm), under 4 covers (unplanted, eucalyptus, poplar and willow) non irrigated from February 2006, 2007 and 2008. Graphs were drawn staggered at each depth for clarity.....	5-64

Figure 34 Available Potassium evolution in soil at 3 depths (10, 30 and 50cm), under 4 covers (unplanted, eucalyptus, poplar and willow) irrigated from February 2006, 2007 and 2008. Graphs were drawn staggered at each depth for clarity..... 5-65

Figure 35 Total Potassium averaged by covers (unplanted, eucalyptus, poplar and willow) and irrigation from samples collected in February 2006, 2007 and 2008. Vertical bars denote 0.95 confidence interval. 5-66

Chapter 6: Evolution of soil water and groundwater chemistry on planted plots irrigated with secondary treated effluent

Figure 1 Cranfield site field trial map, localisation of 24 randomly distributed plots, 3 replicates of 4 covers, unplanted, eucalyptus, willow and poplar, irrigated or not. 6-4

Figure 2 Evolution of TP concentrations on from upstream and downstream samples collected fortnightly from 28/10/06 until the 18/05/08. (vertical bars denote 0.95 confidence interval) 6-10

Figure 3 Evolution of averaged ammonia concentration in soil water at 30 cm and 60 cm depth, under 4 covers, U, W, P, E, irrigated or non-irrigated. (-.-) represents the 1.5 mg-N.L⁻¹ Ammonia consent from UWWD (2003)- (Dashed Zones represent when irrigation was on) 6-12

Figure 4 Evolution of averaged TON concentration at 30 cm and 60 cm depth, under 4 covers, U,W, P, E, irrigated or non-irrigated. (-.-) represents the 11.3 mg-N.L⁻¹ Nitrate standard from Drinking Water Directive (2003) (Dashed area for when irrigation was on) 6-15

Figure 5 Evolution of averaged TN concentration in soil water at 30 cm and 60 cm depth, under 4 covers, U, W, P, E, irrigated or non-irrigated (Dashed zone represent when irrigation was on)..... 6-18

Figure 6 Evolution of ammonia in upstream and downstream groundwater samples from 28/10/06 until 19/05/08. (vertical bars denote 0.95 confidence interval) 6-20

Figure 7 Evolution of TON in upstream and downstream samples from 28/10/06 until 19/05/08. (- -) 11.3 mg-N.L⁻¹ nitrate consent from the nitrate directive used as a benchmark (EC, 1991) 6-22

Figure 8 Evolution of TN in upstream and downstream samples from 28/10/06 until 19/05/08. (Vertical bars denote for 0.95 confidence interval.)..... 6-23

Figure 9 Evolution of averaged K concentration at 30 cm and 60 cm depth, under 4 covers, U, W, P, E, irrigated or non-irrigated. (Dashed zones correspond to period when irrigation was on)..... 6-26

Figure 10 Evolution of K concentrations in groundwater sampled from upstream and downstream the field from 28/10/06 until 18/05/08. 6-28

Figure 11 Evolution of Na concentration in soil water at 30 and 60cm depth under irrigated or non-irrigated plots planted with willow, poplar, eucalyptus or unplanted from July 2006 until February 2008 (-.-) mean Na concentration in effluent 78±50mg-Na/L 6-30

Figure 12 Evolution of Na concentration in effluent used for irrigation from July 2006 to May 2008 on samples collected fortnightly. 6-33

Figure 13 Evolution of Na concentration in groundwater from the 28/10/06 until 18/05/08..... 6-34

Figure 14 Mean of pH with 0.95 confidence interval averaged by cover, and if plot is irrigated and non-irrigated. 6-36

Figure 15 Evolution of averaged EC at 30 cm and 60 cm depth, under 4 covers, U, W, P, E, irrigated or non-irrigated. (Dashed zones represent periods when irrigation was on).... 6-38

Figure 16 Evolution of pH from upstream and downstream samples from 28/10/06 until 11/02/08. 6-39

Chapter 7: Nutrient balances in a WaterRenew system

Figure 1 Thesis outline with nutrients (N, P, K, and Na) fate and interactions between the different compartments of a WaterRenew system (soil, soil water, plant).	7-2
Figure 2 Cranfield site field trial map, localisation of 24 randomly distributed plots, 3 replicates of 4 covers, unplanted, eucalyptus, willow and poplar, irrigated or not.	7-5
Figure 3 Steps for drainage calculation from the theta probes measurements.....	7-12
Figure 4 Steps followed to calculate water storage from DIVINER data.	7-16
Figure 5 Components considered to establish N, P, K and Na balances.....	7-21
Figure 6 Applied N fate in plots with different covers (unplanted, planted with willow, poplar or eucalyptus) irrigated or not after 2 years of experimentation (July 2006 – February 2008) TN in soil was not presented as it was assumed there was no change in soil N store. .	7-22
Figure 7 TN total balances in $t\cdot ha^{-1}$ with TN applied, TN variation in soil from the beginning of the trial to the end, for a layer of 60 cm, TN leached with soil water, TN uptaken by trees after 3 years and TN in soil was not presented as it was assumed there was no change in soil N store. (Vertical bars denote 0.95 confidence interval).....	7-24
Figure 8 Applied P fate in plots with different covers (unplanted, planted with willow, poplar or eucalyptus) irrigated or not after 2years of experimentation (July 2006 – February 2008)	7-27
Figure 9 Total Phosphorus, TP, total balances in $t\cdot ha^{-1}$ with TP applied, total variation of Olsen-P from 0-60 cm profile, TP leached with soil water, TP uptaken by trees after 3 years. (vertical bars denote 0.95 confidence interval).....	7-28
Figure 10 Conceptual model on adsorbed P in soil, interaction between “real” total phosphorus (TP), Aqua regia TP and Olsen-P.	7-29
Figure 11 Applied K fate in plots with different covers (unplanted, planted with willow, poplar or eucalyptus) irrigated or not after 2years of experimentation (July 2006 – February 2008)	7-31
Figure 12 TK total balances in $t\cdot ha^{-1}$ with TK applied, TK leached with soil water, TK uptaken by trees after 3 years.	7-33
Figure 13 Na total balances in $t\cdot ha^{-1}$ with Na applied, Na variation in soil from the beginning of the trial to the end, for a layer of 60 cm, Na leached with soil water.	7-34

Chapter 8: Phosphorus leaching as affected by wastewater application and soil moisture levels

Figure 1 Curvilinear line is fitted Freundlich isotherm through all data points. With the equation $S=138\cdot C^{0.26}$ ($R^2=0.98$ and slope of 0.91 for linear regression between observed data and modelled data). (---) S_{max} graphically adjusted and was assessed at $420\pm60\text{ mg-P}\cdot\text{kg}^{-1}$ of soil.	8-13
Figure 2 Evolution of bromide leaching test on soil columns, High P and Low P applied to keep a constant saturation and Low P applied intermittently. The mass of Br leached is reported with \pm standard deviation calculated from the 3 replicated columns.	8-15
Figure 3 Evolution of bromide leaching test on soil columns, High P and Low P applied to keep a constant saturation and intermittently. The mass of Br leached is reported with \pm standard deviation calculated from the 3 replicated columns.	8-17
Figure 4 Evolution of pH measured from columns fed with high and low P solution intermittently or continuously to maintain saturation.	8-19
Figure 5 Relationship between TP and Phosphate in leachate.....	8-20
Figure 6 Evolution of Cumulative amount of P applied, and Total Phosphorus, TP in leachate from 31/01/08 until 24/06/08. (Vertical bars denote 0.95 confidence interval	8-21

Figure 7 Mean Cumulative TP (mg) leached from columns fed with high and low P solution continuously or intermittently over the period of experimentation. Vertical bars denote 0.95 confidence interval.	8-23
Figure 8 Evolution of volume of leachate and concentration of P in leachate as Phosphate (PO ₄) and Total phosphorus (TP), in mg-P.L ⁻¹ from columns fed continuous or intermittently with high concentrated P solution (40mg-P.L ⁻¹) or low concentrated P solution (4mg-P.L ⁻¹) (vertical bars denote 0.95 confidence interval).....	8-24
Figure 9 Evolution of the regression between cumulative amount of P applied (mg) and cumulative TP leached (mg) for the whole period of experiment under high, low P application to maintain saturation (a, c) and high, low P intermittent application (b, d) per date.	8-25
Figure 10 Evolution of mean TP leached (mg) in relation with cumulative P applied (mg) at a "big scale".....	8-27
Figure 11 Evolution of mean TP leach (mg) in relation with cumulative P applied (mg) at a "small scale".....	8-28
Figure 12 "Tipping buckets" conceptual model. The size of the buckets are different between treatments (low or high P concentrations feeding solutions applied at saturation rates or intermittently.	8-29
Figure 13 Olsen_P (mg-P) in soil profile after irrigation with phosphate solution (4 or 40 mg/L of phosphate) to maintain saturated conditions or intermittently. (---) Heckrath 60mg-P.kg ⁻¹ of soil threshold.	8-30
Figure 14 TP distribution (g of TP) in soil profile after irrigation with phosphate solution (4 or 40 mg/L of phosphate) to maintain saturated conditions or intermittently.....	8-33
Figure 15 Linear regression P applied and Olsen-P built up in soil on an average layer of 60 cm depth.	8-34
Figure 16 Relationship between Olsen-P and aqua regia TP. TP=3.8*Olsen-P+609.9 with R ² =0.77.	8-35

Chapter 9: Modelling framework: WaterRenew system design and decision support tool

Figure 1 Conceptualisation of the WaterRenew design and decision support tool (¹ :GB, 2008) 9-8	9-8
Figure 2 Soil classification according to EC and ESP. (Richards, 1954).....	9-17
Figure 3 Flow diagram of the simulation steps in rearranged WATLOAD2. (the steps described in 4.3 are reported in green).....	9-20
Figure 4 Output of the scenarios compared by default.	9-25
Figure 5 Outputs from WR_model for areas necessary for Godinton site.	9-27
Figure 6 Sensitivity, S calculation for varying PSMD (mm) on area cultivated and area needed for lagoon.	9-29

Chapter 10: Conclusions and recommendations

Figure 1 Nutrients fate and compartments of a WaterRenew system, summary.....	10-6
---	------

LIST OF TABLES

Chapter 1: Introduction

Chapter 2: Wastewater fertigation in renewable energy production: a review of risks and benefits

Table 1 Major constituents of typical domestic wastewater, (arranged from Pescod, 1992., source, UN Department of Technical Cooperation for Development, 1985).....	2-6
Table 2 Comparison of the relative concentrations of N, P, K in different municipal wastes, optimum composition for SRWC and average eucalyptus and poplar nutrients uptake in relation to $n=100$, adapted from Aronsson and Perttu (2001) and Paranychianakis et al., (2006).....	2-10
Table 3 Potential of biomass production and nutrient (N and P) removal by plant species. Source: Paranychianakis et al. 2006.....	2-11
Table 4 Nitrogen budget ($\text{kg N ha}^{-1} \text{ yr}^{-1}$) for each treatment, expressed as mean values ($n= 2$) including N-application via irrigation-fertilisation, leaching loads of $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$ and organic N, net uptake of N in plant shoots, and the estimated combined result of gaseous losses and N to the soil pool. WW=wastewater, LF=liquid fertiliser (source : Dimitriou and Aronsson, 2004).....	2-18
Table 5 Survival of various organisms in selected environmental media at 20-30 °C. Source: WHO, 2006	2-27

Chapter 3: Field trial – Materials and methods

Table 1 Composition of pre-treatment effluent and discharged effluent (average on 2005-2008 bi-monthly analysis, Water Science centre, Cranfield University, personal communication)	3-13
Table 2 Analyses on soil samples and methodology.....	3-23
Table 3 Analyses on soil water samples and methodology.....	3-30
Table 4 Analyses on soil water samples and methodology.....	3-32
Table 5 Factors and model for the statistical analysis.....	3-35

Chapter 4: Growth and water use of and field trial plantation irrigated with secondary treated effluent

Table 1 ANOVA table for stem length from both irrigated and non-irrigated eucalyptus, poplar and willow (in bold, significant factors, $p<0.05$).....	4-15
Table 2 Allometric relationship or linear regression coefficient between leaf biomass and stem diameter measured at 8 cm in mm from ground. ($y=a*x$, a: slope, R^2 : coefficient of determination)	4-18
Table 3 Allometric relationship or linear regression coefficient between wood biomass and stem diameter measured at 8 cm in mm from ground. ($y=a*x$, a: slope, R^2 : coefficient of determination)	4-18
Table 4 Comparisons of the final wood biomass obtained by different calculations methods in odt.ha^{-1}	4-19
Table 5 ANOVA table for log (biomass) from both irrigated and non-irrigated eucalyptus, poplar and willow (in bold, significant factors, $p<0.05$).....	4-20

Table 6 Mean length (L), mean dominant height (MDH), basal area (BA), volume ($V = L \cdot BA$), leaf area index (LAI), calculated dry foliage mass (M_f) oven dry wood mass (M_w) and wood density after two seasons of irrigation. Treatment regimes are irrigated and non-irrigated (mean \pm 0.95 confidence interval).....	4-22
Table 7 ANOVA table for log (biomass) from both irrigated and non-irrigated eucalyptus, poplar and willow (in bold, significant factors, $p < 0.05$).....	4-24
Table 8 ANOVA table for log (LAI) from both upstream and downstream sampling (in bold, significant factors, $p < 0.05$).....	4-27
Table 9 Volume of effluent irrigated (mm), nitrogen, N, and phosphorus, P applied in $\text{kg} \cdot \text{ha}^{-1}$	4-32
Table 10 WUE (g dry biomass per kg of water transpired) on irrigated willow, poplar and eucalyptus with cumulative data at the end of the experiment in February 2008.....	4-34
Table 11 K_c models for willow, poplar and eucalyptus.....	4-35
Table 12 K_c reported in the literature for eucalyptus, poplar and willow.....	4-38
Table 13 ANOVA table for N, P, K, C (%) in leaf material from both irrigated and non-irrigated willow, poplar, eucalyptus (in bold, significant factors, $p < 0.05$).....	4-39
Table 14 P, K, N, C concentrations (%) in eucalyptus, poplar and willow non-irrigated and irrigated.	4-40
Table 15 ANOVA table for N, P, K, C (%) in wood material from both irrigated and non-irrigated willow, poplar, eucalyptus (in bold, significant factors, $p < 0.05$).....	4-42
Table 16 P, K, N, C concentrations (%) in wood of eucalyptus, poplar and willow non-irrigated and irrigated.	4-43
Table 17 ANOVA table for N, P, K, C ($\text{odt} \cdot \text{ha}^{-1}$) in leaf material from both irrigated and non-irrigated willow, poplar, eucalyptus (in bold, significant factors, $p < 0.05$).....	4-43
Table 18 Nutrients uptakes per tree species, irrigated or not, in February 2008 in leaf biomass (mean \pm standard deviation) and total amounts of N, P and K applied during the whole experiment.....	4-44
Table 19 Proportion of nutrients applied effectively uptaken in leaf biomass (%) for irrigated trees.	4-44
Table 20 ANOVA table for N, P, K, C ($\text{odt} \cdot \text{ha}^{-1}$) in wood material from both irrigated and non-irrigated willow, poplar, eucalyptus (in bold, significant factors, $p < 0.05$).....	4-47
Table 21 Nutrients uptakes per tree species, irrigated or not, in February 2008 in wood biomass (mean \pm standard deviation).....	4-48
Table 22 Nutrients uptakes per irrigated tree species, irrigated or not, in February 2008 in leaf and wood biomass, total amounts of N, P and K applied during the whole experiment and % nutrient uptaken compared to nutrient amount applied.....	4-48
Table 23 Potential of biomass production and nutrient (nitrogen and phosphorus) removal of plant species. (Source: Paranychanakis et al., 2006).	4-49
Table 24 NUE, nutrient use efficiencies for wood only after 2 years of cultivation for willow, poplar and eucalyptus irrigated or not. (¹ values from (van Wijk et al., 2003) for forest wood chips. (Mean \pm standard deviation).....	4-51

Chapter 5: Changes in soil chemistry in effluent irrigated willow, poplar, eucalyptus planted field trial

Table 1 Cumulative amounts of nutrients applied by irrigation during the first year from July 2006 until February 2007, and during the second year, from March 2007 until February 2008.	5-7
---	-----

Table 2 Comparison of the relative concentrations of N, P, K in the different municipal wastes, optimum composition for SRWC, Eucalyptus and Poplar nutrients uptake in relation to N=100, adapted from (Aronsson and Perttu, 2001).	5-14
Table 3 Secondary treated effluent average electrical conductivity, pH and sodium concentration on N=27 samples collected bi-monthly from July 2006 until February 2008. (N, number of samples).	5-15
Table 4 ANOVA table for pH of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008. (significant factors in bold)	5-19
Table 5 ANOVA table for log(SAR), log(Na), log(Ca+Mg) of soil samples taken on each plot in February 2006, 2007 and 2008. (Significant factors in bold).	5-21
Table 6 ANOVA table for log(EC) of saturated paste extract from soil samples taken on each plot in February 2006, 2007 and 2008. (Significant factors in bold)	5-26
Table 7 ANOVA table for Na of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008. (significant factors in bold)	5-27
Table 8 ANOVA table for SOM of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008. (significant results in bold)	5-35
Table 9 ANOVA table for TN of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008.	5-44
Table 10 ANOVA table for Olsen's P concentration of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008.	5-48
Table 11 ANOVA table for TP of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008.	5-54
Table 12 ANOVA table for available K concentration of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008. (in bold $p < 0.05$)	5-60
Table 13 Mean available K (mg/kg of soil) grouped by depth in February 2008.	5-62
Table 14 ANOVA table on TK concentration of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008.	5-66

Chapter 6: Evolution of soil water and groundwater chemistry on planted plots irrigated with secondary treated effluent

Table 1 Average composition of effluent used for irrigation. (Relative concentration in relation with N as TN=100, n/a; non applicable)	6-6
Table 2 Comparison of the relative concentrations of N, P, K in the different municipal wastes, optimum composition for SRWC, Eucalyptus and Poplar nutrients uptake in relation to N=100, adapted from Aronsson and Perttu 2001.	6-7
Table 3 Descriptive statistics on phosphate and TP data from irrigated and non-irrigated plots, at 2 depths (30 cm and 60 cm) and under all covers (unplanted, willow, poplar, eucalyptus).	6-8
Table 4 ANOVA table for log(TP) from both upstream and downstream sampling (in bold, significant factors, $p < 0.05$)	6-9
Table 5 ANOVA table for log(NH ₄) in soil water under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p < 0.05$)	6-11
Table 6 ANOVA table for log(TON) under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p < 0.05$)	6-14
Table 7 ANOVA table for log(TN) under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p < 0.05$)	6-17
Table 8 ANOVA table for log(TON) from both upstream and downstream groundwater samples (in bold, significant factors, $p < 0.05$)	6-21

Table 9 ANOVA table for log(TN) from both upstream and downstream groundwater sampling (in bold, significant factors, $p < 0.05$)	6-23
Table 10 Potassium in soil water, general statistics. (Averaged on soil covers, irrigation and depth), in bold the greater when irrigated and non-irrigated measures are compared. .	6-24
Table 11 ANOVA table for log(K) under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p < 0.05$)	6-25
Table 12 Potassium in soil water, general statistics. (Averaged on soil covers, irrigation and depth)	6-27
Table 13 ANOVA table for log(K) from both upstream and downstream sampling (in bold, significant factors, $p < 0.05$)	6-27
Table 14 ANOVA table for log(Na) (log as data has been transformed to assure normal distribution of the residuals) in soil water.	6-29
Table 15 ANOVA table for log(Na) from both upstream and downstream sampling (in bold, significant factors, $p < 0.05$)	6-33
Table 16 ANOVA table for log(EC) under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p < 0.05$)	6-37
Table 17 ANOVA table for pH from both upstream and downstream sampling (in bold, significant factors, $p < 0.05$)	6-39

Chapter 7: Nutrient balances in a WaterRenew system

Table 1 Drainage estimated as cumulative total rainfall (1,071 mm), total irrigated amount and proportion of the drained volume to total water applied to the field from 14/07/06 until 31/12/07.	7-8
Table 2 Average concentrations of different nutrients in soil water from samples collected fortnightly under irrigated plots for all covers, at 30 and 60 cm depth, from 22/07/06 to 11/02/08	7-9
Table 3 Average amount of different nutrients applied by irrigation from 22/07/06 to 11/02/08 under the different covers.	7-9
Table 4 Estimated amounts of leached nutrients on using drained volume as total cumulative rainfall for the period 14/07/06 until 31/12/07 and average concentrations for each nutrient over the same period. % of total applied amount of nutrients leaching amounts represent.	7-10
Table 5 Total rainfall, total irrigated amount, total drainage calculated from soil moisture daily averages (% in volume) differences at 10 cm compared to field capacity (0.55) for the period 14/07/06 until 10/02/08.	7-13
Table 6 Amount of nutrients leached out from the system when drainage is assessed by soil moisture measurements, with field capacity, FC, of 0.55 and a layer of 10 cm of soil considered for the whole period of experiment (July 2006-December 2007).....	7-14
Table 7 Amount of nutrients leached out from the system when drainage is assessed by soil moisture measurements, with field capacity, FC, of 0.55 and a layer of 10 cm of soil considered.	7-15
Table 8 Total rainfall, total irrigated amount, total drainage calculated from water balance with DIVINER data averages for the period 14/07/06 until 10/02/08.	7-17
Table 9 Kc for willow during the 3 years for SRC Adapted from (Jorgensen and Schelde, 2001) and drainage volumes calculated with these Kc for willow.....	7-18
Table 10 Estimated amounts of leached nutrients on using drained volume as result from water balance and DIVINER data and averaged concentrations for each nutrient for the closest date of sampling and DIVINER measurement. Amount of the total amount of nutrients applied effectively leached (%).	7-19

Table 11	Relative comparisons of the different amounts of drainage calculated with the different methods. Rainfall: the simple rainfall assessment, SM: the approach with soil moisture probes data, DIVINER: the approach with DIVINER data.....	7-20
Table 12	Components of TN balance expressed in $t\cdot ha^{-1}$, TN applied by irrigation, TN variation in soil profile from 0-60 cm and SD: standard deviation, TN uptaken by plant (leaf, stem and roots), TN lost by drainage calculated with the DIVINER approach, over the period of experiment from the 14/07/06 until the 11/02/08.....	7-23
Table 13	Components of Total Phosphorus, TP balance expressed in $t\cdot ha^{-1}$, TP applied by irrigation, TP variation in soil profile from 0-60 cm and SD: standard deviation, Olsen-P variation in soil profile from 0-60 cm and SD: standard deviation, TP uptaken by plant (leaf, stem and roots), TN lost by drainage calculated with the DIVINER approach, over the period of experiment from the 14/07/06 until the 11/02/08.....	7-28
Table 14	TK balance expressed in $t\cdot ha^{-1}$, TK applied by irrigation, TK variation in soil profile from 0-60 cm and SD: standard deviation, TK uptaken by plant (stem and roots), TK lost by drainage calculated with the DIVINER approach, over the period of experiment from the 14/07/06 until the 11/02/08.....	7-32
Table 15	Comparison of variation of soil TK and Na during the period of experimentation. (SD for standard deviation) in $t\cdot ha^{-1}$	7-35
Table 16	Summary table of the fate of nutrients applied on the WaterRenew system installed in Cranfield University sewage treatment works (trees: willow, poplar and eucalyptus) ...	7-38

Chapter 8: Phosphorus leaching as affected by wastewater application and soil moisture levels

Table 1	Comparison of maximum P sorption capacities calculated or evaluated from different method, Olsen-P and Freundlich model.	8-13
Table 2	ANOVA table for pH from columns fed with high and low P solution continuously or intermittently (bold when significant $p<0.05$)	8-18
Table 3	ANOVA table for cumulative TP leached (mg) (log) from columns fed with high and low P solution continuously or intermittently (bold when significant $p<0.05$)	8-22
Table 4	Comparison of maximum cumulative leaching P and maximum cumulative P applied for the 4 different treatments.	8-26
Table 5	ANOVA table for Olsen-P distribution. (Significant factors in bold).....	8-30
Table 6	ANOVA table for TP distribution. (Significant factors in bold)	8-32

Chapter 9: Modelling framework: WaterRenew system design and decision support tool

Table 1	Model Processes, inputs and outputs (^(a) Odt : oven dry ton).....	9-11
Table 2	Breakdown of costs. (na ; non-applicable) for one rotation of 30 years.	9-22
Table 3	Financial benefits engendered by implementing a WaterRenew system. (na for non applicable).....	9-23
Table 4	Social and environmental benefits engendered by implementing a WaterRenew system. (na for non applicable).....	9-23
Table 5	clay loam soil physical characteristics.	9-26
Table 6	Annual PSMD for an average year, wet year and dry year.....	9-26
Table 7	average effluent chemical composition at Godinton house.....	9-26
Table 8	Costs comparison between WaterRenew and tertiary treatment unit.	9-27

NOTATION

Al	Aluminium	WUE	Water use efficiency (g.g^{-1})
ANOVA	analysis of variance	WW	wastewater
BA	basal area (m^2)	yr	year
C	Carbon		
Ca	Calcium		
EC	Electrical conductivity (dS.m^{-1})		
ESP	Exchangeable sodium percentage		
ET_0	Reference evapotranspiration (mm)		
FC	Field capacity (%)		
Fe	Iron		
FVI	Fuel value index		
GLM	General linear model		
ha	hectare		
K	Potassium		
K_c	Crop coefficient (-)		
L	Mean length (m)		
LAI	Leaf area index (-)		
LF	Liquid fertilizer		
LR	Leaching requirement		
LSD	Least significant difference		
MDH	Mean dominant height		
M_f	Calculated dry foliage mass (odt)		
Mg	Magnesium		
M_w	Oven dry wood mass (odt)		
N	Nitrogen		
Na	Sodium		
$\text{NH}_4\text{-N}$	Ammoniacal N		
$\text{NO}_3\text{-N}$	Nitrate N		
NUE	Nutrient use efficiency (g.g^{-1})		
odt	Oven dry tonne		
OM	Organic matter		
P	Phosphorus		
PO_4	Phosphate		
PSMD	Potential soil moisture deficit (mm)		
SAR	Sodium adsorption ratio (%)		
SFA	Segmented flow analysis		
SRC	Short rotation coppice		
SRWC	Short rotation willow coppice		
STW	Sewage treatment works		
TC	Total carbon		
TK	Total potassium		
TN	Total nitrogen		
TON	Total oxidised nitrogen		
TP	Total phosphorus		
UWWTD	Urban wastewater treatment directive		
V	Volume ($V = L \cdot \text{BA}$, m^3)		
WFD	Water frame directive		

CHAPTER 1 : INTRODUCTION

1. RESEARCH BACKGROUND

The research described in this thesis is part of a wider EU-LIFE project, the WaterRenew project, which seeks to move forward soil based vegetated wastewater treatment concepts and understanding. The WaterRenew concept can therefore be described as the recovery from wastewater of nutrients which can lead to eutrophication of surface waters, by irrigation of short rotation coppice.

The interest in WaterRenew systems lies in the fact it is integrating two current environmental concerns; firstly the removal of wastewater nutrients by their beneficial use in order to prevent eutrophication and improve or maintain surface water and groundwater quality (requirements of the Water Framework Directive (EC, 2000)); and secondly, the search for renewable energy sources and in particular by biomass production opportunities for bioenergy to achieve the UK's climate change program's aims (EC, 23/01/08).

Such systems have been proven to function properly when studied mainly for N removal and progress has been made on their commercial development in different countries (Paranychianakis *et al*, 2006). However, the factors potentially preventing their sustainable operation have not been identified nor their upper limits quantified with confidence.

Therefore, to what extent is this technology feasible and sustainable in the UK context? Where is it applicable? What are the limiting factors and what are their upper limits before a WaterRenew system's sustainability is put at stake?

2. RESEARCH AIM

A WaterRenew system can indeed be looked at as a unit composed of three main compartments; soil, soil water and plant. There is an important literature available on N and P dynamics and cycling in soil. Nutrients cycling in fertilised vegetated systems has also been studied in depth previously. However, the starting point of most of these studies was to optimise the application of fertilisers to crops; i.e. with the perspective to minimise their application. Then, the starting point in a WaterRenew system is the

opposite; nutrients are abundant and their application not limited. The objective is to maximise the amount of nutrients that can be safely applied to land. Therefore, based on this available knowledge, it is safe to consider that if a WaterRenew system is big enough, it should be able to remove nutrients efficiently (Aronsson *et al*, 2001, Rockwood *et al*, 2004, Paranychanakis *et al*, 2006).

Then, how big does the system need to be to remove efficiently N and P and to operate sustainably for a given site? What are the factors that influence significantly the appropriate running of the system? What are the factors limiting performance of these systems? By knowing them and how they influence the functioning of a WaterRenew system, it will be possible to size them for a sustainable use.

Indeed, the sustainability of such a system will be compromised if at least one of the compartments composing a WaterRenew system is changed irreversibly. The limits can be hydrological with constant runoff or drainage being induced. They can also be chemical if inadequate amounts of nutrients are removed from the effluent applied or if irreversible accumulation of nutrients in soil occurs. Finally, these limits can be physiological with the trees' health being irreversibly compromised.

Thus, the aim of the research is to contribute to the further understanding of soil-vegetated based wastewater systems. This will be in order to identify the factors that must be taken into account to calculate its minimum size in order to optimise both efficient nutrient removal from wastewater and yield for SRC. This minimum size would be the one to ensure the sustainability of the system.

3. THESIS OUTLINE AND METHODOLOGY

In order to pursue this research aim, a field trial was set up at Cranfield University sewage treatment works where *Salix viminalis*, *Populus trichocarpa* and *Eucalyptus gunnii* trees were planted and irrigated with secondary treated effluent from the works.

To tackle more specifically P processes understanding, an independent soil column experiment was also set up.

The chapters are written in paper style following the same structure: introduction, material and methods, results and discussion and conclusion. Each chapter can be summarised: (Figure 1)

- Chapter 1, this present chapter, is a brief introduction to this research.

- Chapter 2 reviews the *a priori* risks associated with this technology that could limit its feasibility, the applicability and sustainability in the light of current available knowledge on wastewater application on land and short rotation coppice.
- Chapter 3 presents the methodology followed to design the experimental field trial at the Cranfield University sewage treatment work, the laboratory methods followed and the statistical model used to analyse results.
- Chapter 4 reports results and discussion on the tree evolution during the field trial.
- Chapter 5 reports results and discussion on soil chemical characteristics during the field trial.
- Chapter 6 reports results and discussion on soil water and groundwater chemical characteristics during the field trial.
- Chapter 7 discusses the nutrient balances on considering nutrients flux from the effluent to soil, soil water, tree, groundwater and atmosphere.
- Chapter 8 presents the experimental methodology, results and discussion of a column experiment conducted to study P dynamics on clay soil under different soil moisture.
- Chapter 9 integrates the observations, measurements and understanding of Cranfield University sewage treatment work field trial into a model, the WR_model. The purpose of WR_model is to help the design and implementation of a WaterRenew system in any location as long as climatic and soil data are available. The model default values are for England and Wales climatic and soil data. Chapter 9 presents and explains WR_model and a simplified sensitivity analysis.
- Finally, Chapter 10 concludes and presents recommendations for further research.

Thesis outline: nutrients fate and compartments of a WaterRenew system

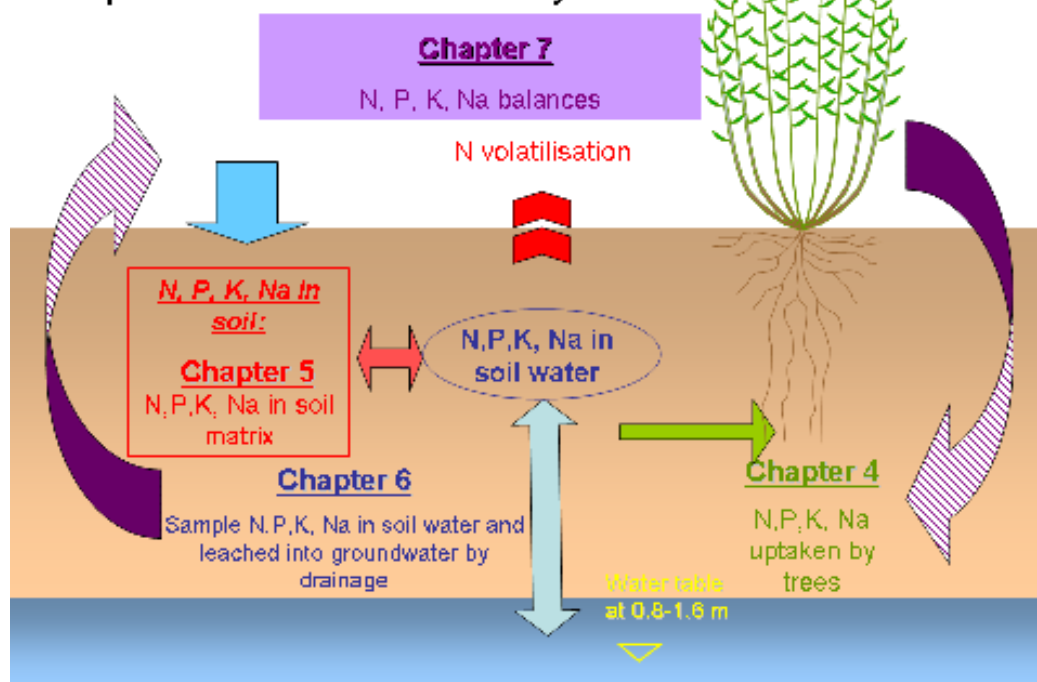


Figure 1 Thesis outline with nutrients (N, P, K, and Na) fate and interactions between the different compartments of a WaterRenew system (soil, soil water, plant).

4. REFERENCES

- Aronsson, P. and Perttu, K. (2001), "Willow vegetation filters for wastewater treatment and soil remediation combined with biomass production.", *Forestry Chronicle*, vol. 77, n^o. 2, pp. 293-299.
- EC (23/01/2008), "Proposal for a directive of the European parliament and the council on the promotion of the use of energy from renewable sources", 2008/0016 (COD).
- EC (2000), *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy*. Office for Official Publications of the European Communities, Luxembourg.
- Paranychanakis, N. V., Angelakis, A. N., Leverenz, H. and Tchobanoglous, G. (2006), "Treatment of Wastewater With Slow Rate Systems: A Review of Treatment Processes and Plant Functions", in *Critical Reviews in Environmental Science and Technology*. Boca Raton: 2006. Vol. 36, Iss. 3 and pg. 187, 73 pgs (eds.), pp. 187-260.
- Rockwood, D. L., Naidu, C. V., Carter, D. r., Rahmani, M., Spriggs, T. A., Lin, C., Alker, G. R., Isebrands, J. G. and Segrest, S. A. (2004), "Short-rotation woody crops and phytoremediation: Opportunities for agroforestry?", *Agroforestry Systems*, vol. 61-62, no. 1, pp. 51-63.

CHAPTER 2 : WASTEWATER FERTIGATION IN RENEWABLE ENERGY PRODUCTION: A REVIEW OF RISKS AND BENEFITS

1. INTRODUCTION

The combination of wastewater polishing with energy crops production is being referred as vegetation filter by Aronsson et al (2001), dendroremediation by Rockwood et al (2004) or slow rate systems (SRS) by Paranychanakis et al (2006). This combination has the potential to optimise both the reuse and recovery of nutrients from wastewater and the level of crop production by reducing fertilizers' requirements (Alker et al., 2003).

A system in which fertigation¹ of fast growing energy crops is associated with wastewater nutrient removal, or tertiary treatment (DEFRA, 2002.b) is referred to a WaterRenew system in this research. To understand what is at stake and to identify which the concerns that need to be taken into account and how they are relevant in the UK context, two questions need to be answered:

- Why is wastewater treated?
- What is the future of renewable energy crops in the UK?

The purpose of this review is to identify what is known and what is not known of risks associated with a WaterRenew system, a system whereby fast growing woody energy crop is irrigated with secondary treated effluent. Thus, the literature was reviewed on this subject firstly, to identify how this technology could have an application in the UK, secondly to describe the major processes involved in nutrient removal by soil and trees and identify the potential risks of nutrients' leaching, and thirdly, to identify the non-nutrients' related risks associated with such systems.

1.1 WHY IS WASTEWATER TREATED?

First, in the UK, urban wastewater treatment obligations and treatment conductance are defined and have to be in accordance with the Urban Wastewater Treatment Directive (UWWTD, 91/271/EEC). Urban wastewater is there defined as "*the mixture of domestic wastewater with industrial wastewater and/or run-off rain water*". This

urban wastewater is treated to ensure the maintenance and improvement of UK water quality as stated in the UWWTD (DEFRA, 2002.b). Not only the treatment is important but also the proper collection, discharge and the correct disposal or re-use of the resulting sludge.

Secondly, this treated urban wastewater has to meet requirements in terms of quality. These requirements are fixed in two European Directives:

- the UWWTD is now largely implemented and establishes which kind of treatment was required for specific areas and specific population. This includes processes from the collection to the discharge of this urban wastewater, as well as which limit concentrations should be respected, in particular for Total Nitrogen and Total Phosphorus (Annex 1, UWWTD, 91/271/EEC)
- the Water Framework Directive (WFD, EC, 2000) is still to be fully implemented. It specifies approaches for point and diffuse sources and programmes with one of the ultimate objectives, to reach “good ecological status” for all waters (Article 4). To achieve good status, nutrients control is required and is specifically mentioned in Annex V of the WFD.

Recent trends in surface water quality in England and Wales were evaluated by reference to data collected by the Environment Agency as part of its General Quality Assessment (GQA) scheme. The GQA provides classification of the chemical quality, biological quality and nutrients’ quality of river water.

In 2008 both the biological quality, indicating the overall health of the rivers, and the chemical quality, indicating the organic pollution, were in general good. For England and Wales, 80 % demonstrated good chemical quality. However, on average for England and Wales, 32 % of rivers demonstrated high concentrations of phosphate (greater than 0.1 mg-P.L^{-1}) and 17 % were found to have high nitrates concentrations (greater than $30 \text{ mg-NO}_3\text{.L}^{-1}$) (cf. Figure 1).

¹ Fertigation is the combination of irrigation and fertilisation.

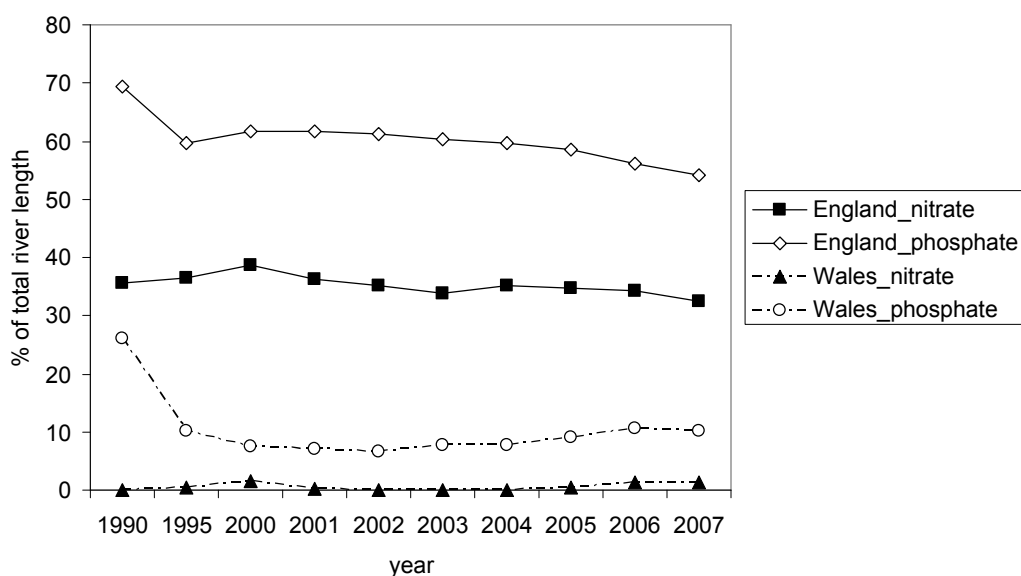


Figure 1 Evolution of nutrients status in England and Wales' rivers. Rivers with nutrients' content classified as "high or above", i.e. with a phosphate concentration greater than 0.1 mg.L⁻¹ and nitrate concentrations greater than 30 mg.L⁻¹. (Source: Environment Agency, 2008)

The situation is better in Wales than in England. For England, phosphate concentration is "high or more" in more than 50 % of the rivers and for nitrates, nearly a third of the rivers have concentrations greater than 30 mg-NO₃.L⁻¹. As a result of the implementation of the nitrates directive that provides specification on the protection of waters against pollution caused by nitrates from agricultural sources (EC, 1991), 68 % of the UK is classified in nitrates vulnerable zones (NVZ) where nitrate application for fertilisation is limited and regulated (DEFRA, 2002a; DEFRA, 2002b; GB, Parliament. Joint Committee on Statutory Instruments., 2008). The situation in 2000 was better compared to 1996 but further improvements are still to be expected (DEFRA, 2002a).

Moreover, concerning phosphorus, although the full implementation of the UWWTD will result in substantial reductions in phosphorus loads, discharges of wastewater without phosphorus removal would continue in sensitive areas, where the population is dispersed or in centres up to 10,000 population equivalents. Further action to reduce phosphorus loads entering surface waters may be required in these areas (WRc, 2002). Therefore, based on the analysis of a number of countries, this phosphorus load reduction should be greater than 70 % in order to achieve the WFD's "good" status. This can only be achieved through the implementation of a combination of limiting/banning the use of Sodium TriPolyPhosphate (STPP) based detergents and improving wastewater treatment (WRc, 2002).

These nutrients, measured in too high concentrations in rivers, come from point and/or diffuse sources, the main contributor (DEFRA, 2002) being agriculture with diffuse nutrients leaching. But, for phosphorus, some studies question the importance of diffuse or agricultural sources compared to point sources, i.e. sewage treatment works (Neal et al., 2005). It even seems that point sources provide a greater risk for river eutrophication² than diffuse sources from agricultural land (Jarvie et al., 2002). Moreover, these nutrients from wastewaters, possibly responsible for eutrophication, are present in a form available for plants' uptake (Rockwood et al., 2004). For this reason, reuse of wastewater on fast growing crops could provide on the one hand wastewater treatment or polishing if the wastewater has been pre-treated and, on the other hand, fertigation of fast growing crops, such as energy crops, to maximize both nutrients' uptake and yield.

1.2 WHAT IS THE FUTURE OF RENEWABLE ENERGY CROPS IN THE UK?

Interest in energy crops as a cost-effective alternative to fossil fuels rose after the first oil crises in the 1970's (Rosenqvist and Dawson, 2005c). Large-scale field trials of short-rotation coppice (SRC) with willow and poplar have been studied since the mid-1980s in the UK (Mitchell et al., 1999/8).

Moreover, the UK ratified the Kyoto Protocol in 1997. This means: *"the UK is legally bound by its Kyoto target to reduce greenhouse gas emissions by 12.5% below 1990 levels in 2008-2012. The UK's climate change programme sets out that the policies in the programme could reduce the UK's emissions by 23% by 2010"* (DEFRA, 2002). Energy crops are a carbon-neutral source of energy and do not contribute to CO₂ enrichment of the atmosphere (Tuskan and Walsh, 2001). Therefore, energy crops can contribute to meeting the UK emissions target under the Kyoto Protocol, and also be a source of renewable energy for EU domestic targets.

In fact, 20% of the EU's energy consumption should be from renewable sources, so the UK share is to increase from 1.5 % in 2006 to 15 % by 2020 (EC, 23/01/2008).

A SRC is defined as a coppice "densely planted, high-yielding varieties of either willow or poplar, harvested on a 2 –5 year cycle, although commonly every 3 years" (DEFRA,

² "The process where excessive nutrients, especially nitrogen and/or phosphorus compounds, cause an accelerated growth of algae and higher forms of plant life. The result of eutrophication is an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned. This can result in low biodiversity with reduction and changes in the range of species of water invertebrates and fish species present in eutrophic waters." DEFRA, 2002.

2002.a). Biomass producers are currently providing 2.3 % of the UK electricity, but to meet renewable energy targets, biomass should provide nearly 30 % of the UK's energy and heat generation (BERR, 2008) and in particular, according to the BERR consultancy report (2008), 25 % of biomass combusted has to derive from crops planted after 1989 for bio fuel production by April 2009. This proportion must increase to 50 % by April 2010, and to 75 % by the period April 2011 - March 2016 (BERR, 2008).

However, despite grants such as the Bio-energy Capital Grants Scheme at its 5th round in 2008 (DECC, 2008) and funds such as the environmental transformation funds (ETF), injecting £1.2 billion for the period 2009-2011 (BERR et al., 2008) that are currently available, energy crop uptake has been low. It can be partially explained by the fact that the sector is still at an early stage of development. For example in Northern Ireland, for willow SRC, cost penalties are imposed to pioneer growers and growth margins are £ 100.ha⁻¹ less than for Swedish willow growers because in Sweden SRWC (short rotation willow coppice) is already commercially set up (Rosenqvist and Dawson, 2005a). Further, SRC has to be able to achieve and maintain high yield to compete with other crops (Rosenqvist and Dawson, 2005c), and, as woody crop, it requires a long term commitment with the risk of a disappointing financial reward (Bullard et al., 2002).

1.3 WHICH WASTEWATER OR WASTEWATERS?

According to the definition given by the UWWTD, (91/271/EEC), the denomination "urban wastewater" comprises 3 types of wastewaters and their mixtures: domestic wastewater, industrial wastewater, and run-off rain water.

This review focuses on the removal of nutrients from domestic wastewater only.

Table 1 (Pescod, 1992) presents the typical chemical composition of domestic wastewaters.

Table 1 Major constituents of typical domestic wastewater, (arranged from Pescod, 1992., source, UN Department of Technical Cooperation for Development, 1985)

Constituents in mg.L ⁻¹	Strong	Medium	Weak
Total solids	1200	700	350
Dissolved solids (TDS)	850	500	250
Suspended solids	350	200	100
Nitrogen (as N)	85	40	20
Phosphorus (as P)	20	10	6
Chloride	100	50	30
BOD ₅	300	200	100

As they can receive run-off rain water from roads, domestic wastewaters can contain high heavy metals concentrations (cf. Section 3.3).

On focusing on N and P, as primary treatment is physical with the removal of large objects and sedimentation, N and P present in organic and inorganic forms in solution or suspended will remain in the effluent untreated (Hammer and Hammer, 2008.). N will be present mainly as ammonia, and organic N will mineralise by ammonification into ammonia (Montuelle et al., 1992).

During the secondary treatment or biological treatment, organic matter present in wastewater is fed to microorganism and therefore broken down (Hammer and Hammer, 2008.). In particular, ammonia present in wastewater is transformed to nitrites then nitrates by nitrifying bacteria in aerobic conditions. For this reason, ammonia content of secondary treated effluent is generally low and the major contribution of total nitrogen (TN) will be in the form of nitrate (Hammer and Hammer, 2008.). Table 1 presents TN to range typically between 20-85 mg-N.L⁻¹. Moreover, the UWWTD discharge consent for ammonia are 10 mg.L⁻¹ for non sensitive areas, 5 mg.L⁻¹ in winter and 3 mg.L⁻¹ in summer for sensitive areas³ (DEFRA, 2002.b).

³ Sensitive areas are defined in the UWWTD as "An area designated under the Directive according to three criteria: (a) waters that are, or have the potential to become, eutrophic if no protective action is taken. (b) drinking water sources that contain or could contain more than 50mg/l of nitrate if no protective action is taken. (c) waters in need of protective action to meet the requirements of other Directives. Wastewater discharges over 10,000 PE that pollute sensitive areas need treatment that relates to the designation criterion or criteria."

P is present in domestic sewage at concentrations ranging from 5-10 mg-P.L⁻¹ under suspended and soluble forms (Watanabe et al., 1999). If no further treatment is conducted, P present in wastewater would not be removed. The UWWTD P discharge consent is 2 mg-P.L⁻¹ of TP for sewage treatment work greater than 10,000 p.e⁴. and 1 mg-P.L⁻¹ of TP for works greater than 2,000 p.e. (DEFRA, 2002.b).

For both N and P, they are mainly under mineral forms in wastewater i.e. plant available and therefore eutrophic forms. Nitrate for N and phosphate for P and effectively the forms under which they are applied in industrial fertilisers (MAFF 2000). However, organic N and P present in the secondary treated effluent will also mineralised and therefore have to be accounted for potentially eutrophic N and P.

The impact of their presence for soil and plant will be assessed in paragraph 3.2.

Therefore, the components needed to be removed from secondary treated wastewater are nutrients N and P, heavy metals and pathogens. UWWTD (DEFRA, 2002.b) defines tertiary treatment as nutrient removal and/ or disinfection and that is what WaterRenew system would intend to do with a major focus on nutrient removal.

1.4 FEASIBILITY AND SUSTAINABILITY OF FERTIGATION OF ENERGY CROPS WITH DOMESTIC SEWAGE ?

Combination of fertigation and phytoremediation, referred to in this paper as a WaterRenew system, is not a new idea and commercial adoption has taken place in New Zealand, the US and Sweden (Paranychianakis et al., 2006).

The economics were assessed by Rosenqvist and Dawson (2005b) for wastewater irrigated SRWC in Northern Ireland. The conclusion was encouraging as there is definitely an added value for SRC because of wastewater treatment capacity.

However, the safety of this process for the environment and public health has to be established. What are or can be the impacts or effects of this WaterRenew system on the environment? How can it be implemented and then assessed? How can it be modelled?

⁴ p.e.: population equivalent "The unit of measure used to describe the size of a waste water discharge. 1 population equivalent is the biodegradable load (matter) in waste water having a 5-day biochemical oxygen demand (BOD) of 60g of oxygen per day. Population equivalent doesn't necessarily reflect the actual population of a community (or Agglomeration)".(DEFRA, 2002.b)

Scott et al. (2000) identified four main types of risks associated with wastewater irrigation of crops grouped into 2 categories:

- 1) Nutrients focused:
 - Leaching of nutrients and/or other organic components into ground water.
 - Increased atmospheric emission of greenhouse gas by denitrification of waste Nitrate applied on soil.
- 2) Non-nutrients focused:
 - Public health risks associated with the presence of pathogens in wastewater.
 - Accumulation of heavy metal or other hazardous materials that will be stored in the trees that may be released upon burning or accumulation in soil and the associated risk of leaching into groundwater.

Therefore, in this chapter, the literature will be reviewed around these two focuses to identify the potential risks and to try to assess how sustainable and feasible this technology would be in the UK context and for which type of sewage treatment works.

2. NUTRIENTS FATE IN WASTEWATER IRRIGATION OF ENERGY CROPS: WHERE ARE THE RISKS?.

2.1 TREE RESPONSE TO NUTRIENTS

2.1.1 Willow, poplar and eucalyptus in the UK: water use, yield and cultural practices

The principal species planted on short rotation are *Eucalyptus*, *Pinus*, *Populus* and *Salix* (Mitchell et al., 1999; Tabbush et al., Revised, in press). Tabbush et al. (Revised, in press) recommend specific varieties of willow and poplar for SRC in the UK as yield should be over 10 oven dry tonnes ($\text{odt} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$) to be economically viable for energy use, composting or fines for board manufacture.

Many crop plants use the ratio 270–450 kg of water per kg of net biomass production. Tree water transpiration is directly related to biomass growth and the tree's water use efficiency (Licht and Isebrands, 2005), and the trees' capacity to uptake nutrients from soil solution is directly correlated to the amount of water they can extract (Mengel, 1985). Paranychianakis et al., (2006) explains that the application of hydraulic loads of wastewater to meet plant water demands generally exceeds vegetation capacity for

nutrient uptake and removal and that for low nutrient level wastewater as pre-treated wastewater, low water use efficiency (WUE) species should be chosen.

- Poplar sp.

In particular, poplars are known to take up between 20 and 50 kg of water per tree per day once mature (Dickmann et al., 2001) and models exist so that poplar water consumption can be accurately estimated as a function of the tree size (i.e. diameter, height, and leaf area).

Generally, the best results with poplar coppice in the UK and the USA are achieved for spacing between 5,000 and 7,000 trees ha⁻¹ and harvest cycles of 3-4 years (Mitchell et al., 1999/8).

(Armstrong et al., 1999) achieved the highest yields (13.6 odt.ha⁻¹) on three sites in UK with different soil types and annual rainfall for *Populus trichocarpa* × *P. deltoides* “Beaupré”, *Populus trichocarpa* × *P. deltoides* “Boelare” and *Populus trichocarpa* “Trichobel” when they were planted with a spacing of 1.0 m × 1.0 m and a four year cutting cycle.

- Willow sp.

(Martin and Stephens, 2006) implemented lysimeter trials for the investigation of water use efficiency (WUE defined as dry matter production per unit of water used) of willow sp. in different soil type and levels of compaction, and under different watering and amendment regimes with organic matter and fertiliser. They found that in conditions of no water stress, seasonal evapotranspiration (ET) was increasing from 360 kg per tree in the first year to 1,200 kg per tree in the third year and the maximum being 13.6 kg per tree per day for sandy loam with no water stress.

(Mitchell et al., 1999/8) reported that in general, planting rates between 5,000 and 20,000 plants.ha⁻¹ are used for willow and poplar crops with corresponding rotation periods of 3 to 5 years (Ledin and Willebrand, 1995).

- Eucalyptus sp.

Interest in introducing eucalyptus as energy crops in the UK has been growing since the 80's (Purse and Richardson, 2001) with the Forestry Commission establishing eucalyptus species trials between 1980 and 1985 (Evans, 1983).

Purse and Richardson compiled information about the Forestry Commission eucalyptus trials in eight locations in the UK since October 2000. According to them,

yields of 10-15 odt.ha⁻¹.yr⁻¹ on 8-10 years rotations are realistic in the UK and even shorter rotation may be possible with the more vigorous species on productive sites. Two of the most interesting candidates, both practically and economically, are *Eucalyptus nitens* and *Eucalyptus gunnii* and with a plantation density ranging from 1,333 to 3,700 plants ha⁻¹.

Morris and Collopy (1999) measured by the heat pulse method, that the average single tree water use varied from less than 10 L.day⁻¹ in winter to over 30 L.day⁻¹ in summer.

Therefore, considering only SRC, from the literature, the reported yields for the willow, poplar and eucalyptus were over the 10 odt.ha⁻¹.yr⁻¹, economical viability threshold defined by Tabbush et al. (Revised, in press).

2.1.2 SRC of willow, poplar and eucalyptus: nutrients' fate

Aronsson and Perttu (2001) presented Table 3 comparing relative concentrations of the three macronutrients N, P, K in different municipal wastes. The table has been completed with nutrients' uptake ability for eucalyptus (FAO, 1985) and poplar (*P. trichocarpa*) after leaf fall (Moffat et al., 2001).

Table 2 Comparison of the relative concentrations of N, P, K in different municipal wastes, optimum composition for SRWC and average eucalyptus and poplar nutrients uptake in relation to N=100, adapted from Aronsson and Perttu (2001) and Paranychanakis et al., (2006).

Element	Untreated wastewater	Tertiary treated wastewater	Average sludge in Sweden	Average landfill leachate in Sweden	Optimum composition for SRWC	<i>Eucalyptus urophylla</i> hybrids (Brazil 7yrs)	<i>Populus trichocarpa</i>
N	100	100	100	100	100	100	100
P	17.5*	≈4.5*	73*	0*	14* ⁵	8	15
K	64	≈60	9	54	72	57	45

Willow SRC, (SRWC) was vegetation filters far more studied than poplar and eucalyptus. One of the reasons for this is that willow nutrients requirements' match very well average wastewater composition, especially for phosphorus (Table 3).

Paranychanakis et al (2006) compiled biomass production and N and P removal of *Eucalyptus sp*, *Salix sp*, and *Populus sp* (Table 4). The equivalent size of the sewage treatment works (STW) a SRC of each species could cope with per hectare

considering their N and P removal capacity separately was calculated. The calculation considered an average wastewater of $TN=40 \text{ mg-N.L}^{-1}$, $TP=2 \text{ mg-P.L}^{-1}$ and a daily average water consumption of 150 L.p.e.^{-1} . As P concentration in wastewater is lower than N, if only P is considered, the number of population equivalent each hectare can cope with charge is much higher for all tree species (Table 4) than when only N is considered. Indeed for eucalyptus species, it is nearly twice more, for poplar species, nearly 5 times and for willow species, 3 times more. Therefore, calculations for N should be considered.

Table 3 Potential of biomass production and nutrient (N and P) removal by plant species. Source: Paranychianakis et al. 2006.

Plant species	Age of crop	Biomass (t/ha)	N removal (kg/ha)	P removal (kg/ha)	Reference	Size STW for N (p.e./ha)*	Size STW for P (p.e./ha)*
<i>Eucalyptus botryoides</i>	3	39.7	425	42	Guo et al. (2002)	65	128
<i>Eucalyptus globulus</i>	3	64.7 to 80	651	55	Guo et al. (2002) Ducan et al (1998)	99	167
<i>Eucalyptus ovata</i>	3	45.5	401	37	Guo et al. (2002)	61	113
<i>Eucalyptus camaldulensis</i>	2	4.5	-	-	Tzanakakis et al. (2003)	-	-
<i>Eucalyptus grandis</i>	3	36.1	-	-	Ducan et al (1998)	-	-
<i>Populus sp. (hybrid poplar)</i>	4	44 to 111	241-420	41 to 105	Heilman and Norhy (1998)	28-48	94-240
<i>Populus sp. (hybrid poplar)</i>	3	4.82 to 8.08	110.4	18	Moffat et al. (2001)	17	55
<i>Populus trichocarpa</i>	3	2.19 to 5.45 **	72.9	11.2	Moffat et al. (2001)	11	34
<i>Salix Sp. (various willow clones)</i>	1	15 to 22	75 to 86	10 to 11	Adegbidi et al. (2001)	34-39	91-100
<i>Salix viminalis (hybrid willow) 1st rotation</i>	3	35.08	-	-	Labrecque and Teodorescu (2003)	-	-
<i>2nd rotation</i>	3	58.80	389	46.1		59	140

⁵ Lines inverted for P and K in original table from Aronsson et al (2001) (pers.com).

* According to N or P removal capacity, we calculated the equivalent size of the sewage treatment work (STW) a SRC for each species considering an average wastewater of $TN=40 \text{ mg-N.L}^{-1}$, $TP=2 \text{ mg-P.L}^{-1}$ and a daily average water consumption of 150 L/p.e. **Biomass assessed after leaf fall.

Conclusion

UK climatic conditions presented encouraging yields for SRC of willow, poplar and eucalyptus. Furthermore, there is a good match between average wastewater composition and SRC nutrients demand (Table 3). Despite a less optimum match for eucalyptus and poplar than for willow (Table 3), on considering only N removal, eucalyptus would be the more surface efficient as it can treat the equivalent of more than 60 p.e.ha^{-1} and only more than 40 p.e.ha^{-1} for willow and more than 11 p.e.ha^{-1} for poplar species.

2.2 SOIL ROLE IN NUTRIENTS REMOVAL

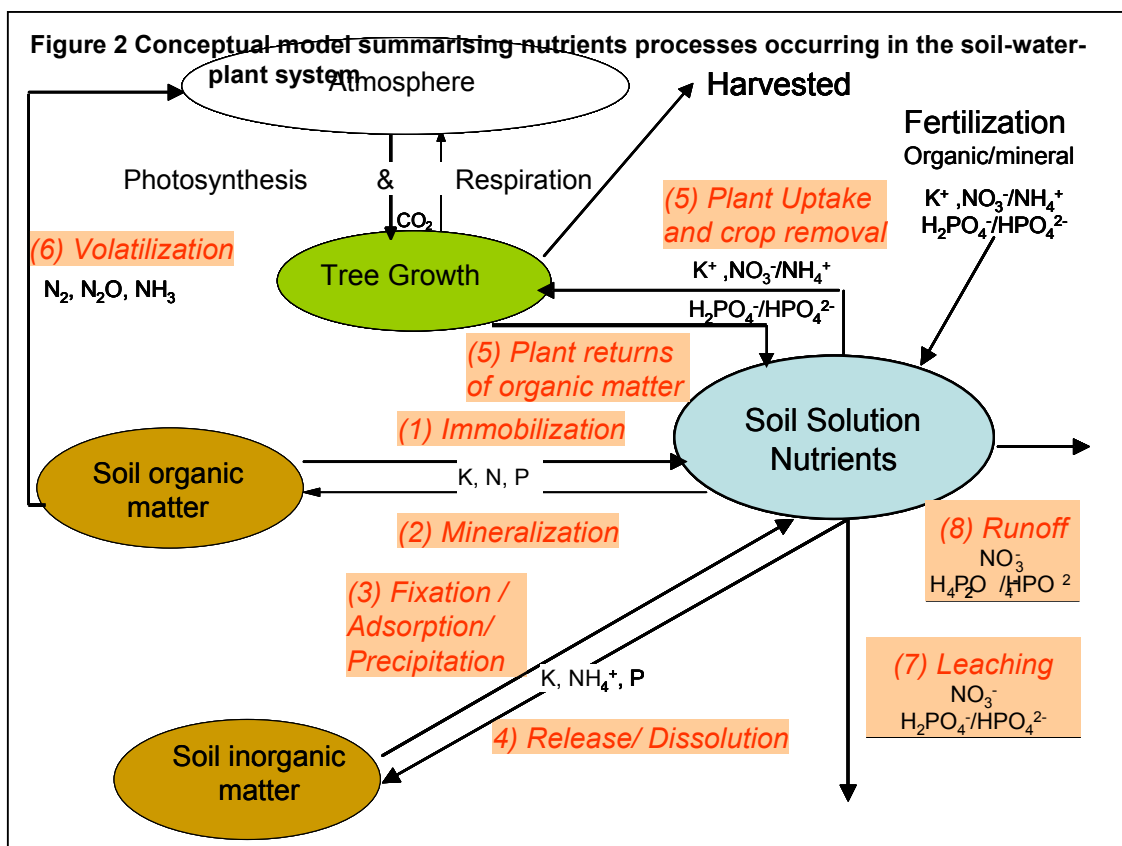
The trees in the WaterRenew system have the capacity to uptake and remove nutrients applied by fertigation. In this section, literature is reviewed to identify the importance of soil in the system.

2.2.1 Soil capacity to retain and transform nutrients

Nutrients' dynamics in fertilised vegetated systems' soils have been exhaustively studied and many reviews are available on N, P and K cycles. (e.g. N cycle by Stevenson (1986), P cycle has been reviewed by Pierzynski (2000), K cycle, by Sparks and Huang (1985). There is no ambition here to cover it again. However, the purpose in this section is to present a simplified conceptual model emphasizing the part of these dynamics that is useful for phytoremediation of domestic wastewater by trees. Moreover, the starting point of most of these studies was to optimise the application of fertilisers to crops; i.e. with the perspective to minimise their application. Then, the starting point in a WaterRenew system is the opposite; nutrients are abundant and their application not limited.

2.2.2 Conceptual model of soil “treatment” capacity

The processes N, P and K in the soil-water-plant system irrigated with domestic wastewater are identified and a simplified summary of the processes is presented. Irrigation with secondary treated wastewater will bring N, P and K under organic forms and mineral forms: K^+ , NO_3^-/NH_4^+ , $H_2PO_4^-/HPO_4^{2-}$. Organic forms will eventually mineralise by decomposition and bacterial digestion and contribute to the mineral pool.



Once nutrients are brought into soil by fertigation, they can be included in three compartments: soil, soil water and plant. The main processes were identified from the literature in terms of nutrients dynamics in soil. Processes presented in Figure 2 are briefly explained in the following paragraphs in order to identify the potential risks of nutrients loss from the system.

1. Immobilisation/ assimilation in soil organic matter

N, P and K, in both organic and mineral form, brought by fertigation can be assimilated by soil micro-organisms into soil organic matter, i.e. litter and humus. They are temporarily immobilised until organic matter is re-mineralised.

2. Mineralisation

The nutrients once incorporated into organic matter can still be re-released because of decomposition by bacteria and fungi in the soil. For N, organic N can be mineralised into NH_4 and NO_3 forms (Rowell, 1994). P and K will be under soluble forms i.e. mainly ortho-P, (Pierzynski, 2000) and K^+ (Brady and Weil, 2001).

3. Adsorption, fixation or precipitation on clay or soil minerals (occlusion)

For N, nitrates are not fixed or adsorbed on soil particles or matrix. However, NH_4 can be adsorbed and contribute to some extent to soil cation exchange capacity⁶, CEC. But NH_4 can also be nitrified by bacteria into first nitrites and then nitrates.

Phosphate can be completely occluded and taken out of the soil solution and not be participating in the dynamics. They can also precipitate with Ca^{2+} , Al^{3+} or Fe^{3+} and become non available for plant. For soil with high cation exchange, precipitation can be the predominant mechanism through which P availability to plant is reduced (Tunesi et al., March 1999)

K^+ can be adsorbed to soil particles and be exchanged as part of soil CEC.

4. Release from soil inorganic material

Phosphates and potassium solubilise from clay and mineral soil matter into soil solution by dissolution processes or because pH, redox or physico-chemical conditions change.

5. Plant uptake

⁶ Soil cation exchange capacity is defined as the proportion of cations “held by electrostatic forces on soil particle surfaces to balance the surface negative charge” (Rowell, 1994)

NH_4 , NO_3 , PO_4 and K^+ are the forms under which plant roots and soil microbial population can uptake N, P and K.

6. Volatilisation

Volatilisation only concerns N. Nitrates can be denitrified by bacteria into N_2 under anaerobic condition and then volatilised into the atmosphere. However, in the process, it can produce N_2O , a major greenhouse gas (Yung et al., 1976) and promote the destruction of the stratospheric ozone layer (Liu et al., 1977).

Then, NH_4 can also under alkaline conditions be converted into NH_3 , which will also volatilise and even though it is not a greenhouse gas, it can represent an environmental concern as olfactory pollution. But as NH_4 concentrations are very low in secondary treated sewage, NH_3 volatilisation is unlikely to be a problem.

7. Leaching

All the nutrients applied by irrigation can be leached if not fixed, adsorbed, uptaken by plants or volatilised. For nitrates and phosphates, it is problematic as they can cause eutrophication of other water compartments.

8. Runoff

Mander et al (2000) identified the major factors affecting nutrients runoff in both the entire catchment and its agricultural sub catchments as the change of land use (including fertilisation intensity), soil parameters and water discharge. The rate of fertilisation was identified as the most important factor affecting nitrogen runoff in small agricultural sub-catchment, while land-use pattern is more important in larger mosaic catchments. Avoiding runoff results in avoiding diffuse pollution and this can be achieved by the establishment of ecotechnological measures (e.g. riparian buffer zones and buffer strips, constructed wetlands) (Mander et al., 2000).

2.2.3 Soil processes and susceptibility to environmental risks

We will consider the processes described in Figure 2 (2.2.2) focusing for each element on the ones potentially leading to environmental risks.

1. Processes involving nitrogen potentially presenting an environmental risk

- Immobilisation/ mineralisation

N, P and K brought by fertilisation will be incorporated into soil organic matter, i.e. litter and humus. They are temporarily immobilised until organic matter is re-mineralised. But once mineralised, N is under nitrates and ammonia forms and is therefore soluble and susceptible to leach. Therefore, it is important to know the rate of these turnovers in order not to over fertilise SRC and minimise leaching risks.

Soil organic matter is constituted of microbial cells which are bacteria, fungi and protozoa. It is also composed of very stable fulvic acids, humic acids, and non-humic material and biomass with a much faster turnover (Mengel, 1985). Berg et al., (2005) quantified the amounts of N sequestered annually. They ranged from ca. 1–2 kg-N.ha⁻¹.yr⁻¹ under nutrient-poor boreal conditions to about 30 kg-N.ha⁻¹.yr⁻¹ in temperate, more nutrient-rich forests.

Trees' uptake capacity depends on external characteristics like climate, season, type of soil and cultural practices (Paranychiakis et al, 2006). N removal ranges from 75 kg.ha⁻¹ (willow) till over 650 kg.ha⁻¹ (eucalyptus) per year (cf. Table 2) and mineralisation accounts for little in N budget.

- Volatilisation of N into N₂, N₂O and NH₃

Denitrifier bacteria need anaerobic conditions to reduce nitrates into nitrous oxide and then into N₂ (Rowell, 1994). In a WaterRenew system, if irrigation is not applied to maintain well watered conditions in soil, anoxic zones could develop and therefore, the conditions are created for denitrifying bacteria to operate and produce greenhouse gas nitrous oxide. Moreover, a research on N₂O and N₂ emissions from loamy clay soil column under different water regimes and straw amendment (Cai et al., 2001) reported the highest emission of N₂O from soil that was non-amended and maintained at 65-70 % of water holding capacity and higher than from soil under continuous flooding or under a cycle of flooded/ drained conditions. It was also confirmed in this study that N₂O-N was mainly coming from nitrates and not NH₄ by marking the applied urea with ¹⁵N.

So far, research conducted on wastewater fertigation on SRC assessed N volatilisation using mass balance. N volatilisation after application of biosolids, animal slurry or poultry litter, have been studied and the results of these researches will be considered to assess the importance of the risk of N volatilisation on a WaterRenew system. However, as poultry litter or animal manure is not treated, their N composition is close to raw domestic sewage; i.e. with N predominantly under ammoniacal form and as a

very low proportion of nitrates.

Denitrification and nitrification are considered the major sources of nitrous oxide (Sahrawat and Keeney, 1986). Sahrawat and Keeney (1986) identified, apart from N availability in soil, high soil water content and drying, low oxygen supply as factors enhancing denitrification. (Marshall et al., January 2001) quantified the fate of N (poultry litter) applied on different sites in southern US. They found that plant uptake was the largest use of applied N, averaging 43 % of applied N, whereas the combination of losses due to NH_3 volatilisation and denitrification, was only 6 % of applied N on average and the remaining 51 % was leached into groundwater. In another study (Marshall et al., January 2001), a sharp increase in NH_3 volatilisation rate was measured during day 1 to 3 after litter application at all sites studied. However, volatilisation rates rapidly decreased to normal levels within 10 days rate peaks of $2.8 \text{ kg } \text{NH}_3\text{-N.ha}^{-1}\text{.d}^{-1}$ in year 1 and $2.2 \text{ kg-NH}_3\text{-N.ha}^{-1}\text{.d}^{-1}$ in year 2. They concluded that overall, N losses due to NH_3 volatilisation were less than expected based on previous studies and therefore a relatively minor component of the N cycle. Therefore, as secondary treated wastewater presents very low ammonia concentration, NH_3 volatilisation will be very limited.

Hence, volatilisation mainly takes place just after application of N, which in general cultural practices, is usually once a year (Marshall et al., January 2001). As a fertigation system can be working continuously all year long, reductive and anaerobic conditions favourable to volatilisation might develop if the system is not well run. Therefore, volatilisation might become significant by occurring continuously and might need to be assessed.

- Leaching/ runoff

Aronsson et al. (2000) reported a moderate effect of intensive SRC of willow fertilised at rates ranging from $0\text{-}153 \text{ kg-N.ha}^{-1}\text{.yr}^{-1}$ on N groundwater concentration and for this reason, major N leaching to groundwater was not occurring in intensive SRWC.

Aronsson and Perttu (2001) and Aronsson and Bergstrom (2001) identified the factors influencing NO_3 leaching as soil type (trial in lysimeters with clay or sand), plant development stage, N application rate and irrigation rate. Even if the first year presented high nitrate leaching, the second and third years presented low to negligible leaching (3 kg-N.ha^{-1} from clay and less than 1 kg-N.ha^{-1} from sand lysimeters for Year 3). Harvest of plants after the second growing season did not affect $\text{NO}_3\text{-N}$ leaching

loads during the third year. The factors with strong influence on leaching were identified as soil type, with sand leaching more nitrates, and N application rate (as kg-N.ha⁻¹), whereas irrigation rate as hydraulic loads had only a slight effect (Table 5). Hence, Aronsson and Bergstrom (2001) advise to dose wastewater application according to N application (kg-N.ha⁻¹) rather than hydraulic loads. Dimitriou and Aronsson, (2004) validated this recommendation by trying to push the system to determine its limits ("to crash it") by applying 320 kg-N.ha⁻¹ under different forms and for 8 days in a lysimeter trial (Table 5).

Table 4 Nitrogen budget (kg N ha⁻¹ yr⁻¹) for each treatment, expressed as mean values ($n= 2$) including N-application via irrigation-fertilisation, leaching loads of NO₃-N, NH₄-N and organic N, net uptake of N in plant shoots, and the estimated combined result of gaseous losses and N to the soil pool. WW=wastewater, LF=liquid fertiliser (source : Dimitriou and Aronsson, 2004)

	<i>Clay WW</i>	<i>Clay LF</i>	<i>Sand WW</i>	<i>Sand LF</i>
N-application	320	320	320	320
NO ₃ -N leaching	-71	-70	-82	-106
NH ₄ -N leaching	-2	-4	0	0
Org-N leaching	-7	-7	-8	-10
N-uptake shoots	-115	-110	-44	-36
N not accounted for	-125	-129	-186	-168
Σ	0	0	0	0

However, this trial demonstrated that high level of N leaching resulted from high levels of application and no short-term damage to plants was noticeable. Therefore for N, leaching risk happens when mineral N applied cannot be taken by soil organic matter or plant roots and become organic N (Rowell, 1994).

2. Processes involving phosphorus potentially presenting an environmental risk

As fertilizer application is usually calculated on N requirement, when biosolids, or manure or litter or sewage are applied, too much P is applied and accumulates in soil and there can be a risk of leaching (Sharma et al., 2006; Sharma et al., 2006). However, P leaching processes are more complex than N leaching process and they are going to be developed in further detail.

Once P is applied as soluble P, because of its relatively low solubility and high affinity for soil particles (Pierzynski, 2000), P will tend to adsorb onto soil particles if it can (Figure 4). But P sorption is limited as soil P sorption capacity is finite, therefore to ensure wastewater system sustainability, this sorption capacity has to be considered.

P can be applied in solution either as soluble P or Ca-bound P, both of which are extremely soluble. And it can enrich either pool in soil (Van der Zee and Gjaltema, 1992). P will enter the soil compartment mainly under soluble P form and could runoff with water, or not enter the soil system because of erosion of soil sediments on which P will have sorbed. Soluble P can be in 2 forms; dissolved or more labile and suspended or moderately labile. Soluble P can then be uptaken by plants (Van der Zee and Gjaltema, 1992) or immobilised in soil organic matter at a smaller rate. It can be sorbed on sediment and join the soil solid phase until a limit is reached (McGechan and Lewis, 2002). Also, instead of being sorbed, it could leach because of bypass flow (Van der Zee and Gjaltema, 1992) or leach into groundwater (McGehan et al, 2002).

Soil solid P can be found in different forms: i) P in primary minerals, Ca-bound and very soluble, ii) P in secondary minerals clay Fe and Al oxides bound and moderately soluble, iii) P occluded in Fe and Al minerals and extremely insoluble. This P can then interact with the soluble P pool by either being desorbed into soil solution, or by being mineralised under microbiological action of phosphobacteria (Kundu and Gaur, 1980). It can also leave soil by eluviation, i.e. loss in sediment form in occlusion in soil particles (Brady and Weil, 2001).

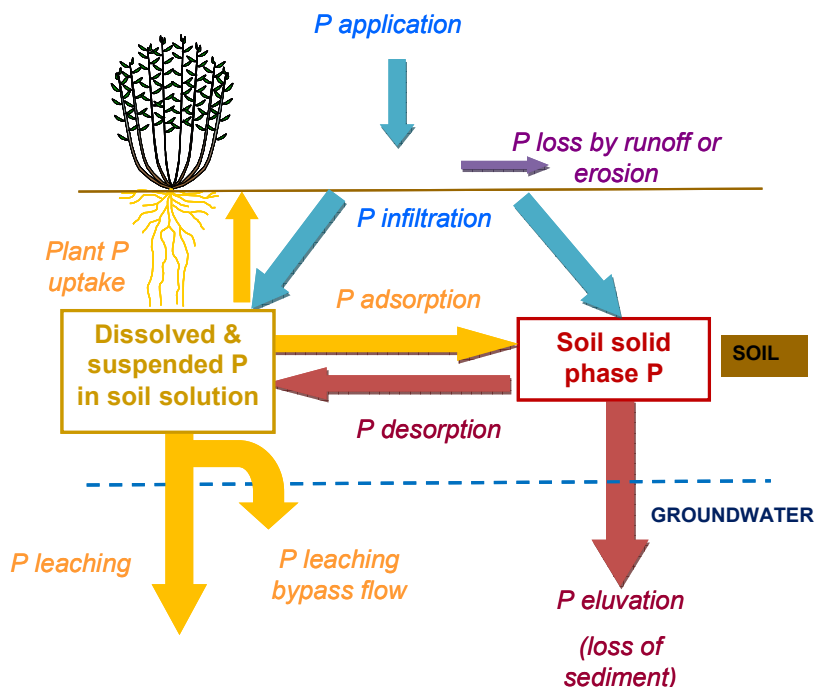


Figure 3 A generalised scheme of phosphorus dynamics in a WaterRenew system.

Thus, to prevent leaching to happen, soluble P has to be adsorbed. However this process is limited by the soil phosphorus sorption capacity (Rowell, 1994). As P can be adsorbed onto different sites (Ca, Al, Fe and organic matter) with different sorption strength, different approaches were developed to assess soil phosphorus sorption capacities (McGehan, 2002). Sims and Pierzynski (2005) have found a consistent pattern showing increases in soluble and de-sorbable P in both soil extracts and in runoff when soil test P values increase beyond the agronomical optimum range values. Pautler and Sims (2000) showed that the degree of saturation of soil in phosphorus can be correlated to soil test phosphorus (STP, Mehlich-1 soil test) and this STP can be used to identify fields, farms and watersheds where non-point source P pollution could become an environmental issue. Because we want to determine the maximum of a sorption process, the general approach to determine P sorption capacity is through conducting an isotherm sorption experiment and fitting either the Freundlich model or the Langmuir model to estimate this maximum sorption capacity. Indeed, soil samples are put in contact with solutions of different P concentration until equilibrium is reached and the way P sorbed according to the P concentration in situation is measured

(Rowell, 1994). Heckrath also proposed a P content of 60 mg.kg^{-1} of soil of Olsen-P⁷ as a threshold after which P sorption onto soil in the solid phase will decrease significantly allowing P to leach (Heckrath et al., 1995). This was validated also on sandy soils by Shepherd and Withers, (2001) where even after applying $240 \text{ kg-P.ha}^{-1} \cdot \text{year}^{-1}$, as liquid digested sewage sludge for 3 years on lysimeters maintained bare, no significant P increase in drainage was observed and Olsen-P remained under 60 mg.kg^{-1} of soil (from originally 31 mg.kg^{-1} of soil to 55 mg.kg^{-1} for loamy sand after application of $240 \text{ kg-P.ha}^{-1} \cdot \text{year}^{-1}$ for 3 years and from originally 30 mg.kg^{-1} of soil to 40 mg.kg^{-1} for sandy loam after application $60 \text{ kg-P.ha}^{-1} \cdot \text{year}^{-1}$ for 3 years). Shepherd et al (2001) concluded there were no major risks associated with sludge biosolid application at operational rates. However, the Heckrath threshold was not reached; therefore, the long-term effect is still not forcastable from this experiment. (Shober and Sims, 2003) reported also other thresholds used in different states of the USA and among them, a 100 mg.kg^{-1} of soil of Olsen-P.

Another assessment of P sorption capacity has been developed for non-calcareous soil by van der Zee and van Riemsdijk (1988) as the degree of phosphorus saturation (DSP) where P, Fe and Al are extracted in oxalate ammonium. (Sinaj et al., 2002) advised to stop P application before DSP equals 25 % or leaching will occur. However, other studies where treated effluents were irrigated to a tree plantation or to land, these P sorption capacities failed to predict P leaching. Isotherms underestimated soil P sorption capacity (Falkiner and Polglase, 1999; Falkiner and Polglase, 1997) in Australia and Lin and Banin, (2006) in Israel on predicting P leaching much earlier than it was effectively observed on the field. On the other hand, in some other cases, leaching was observed well before sorption capacity was filled (Litaor et al., 2003). Litaor et al. did not manage to link efficiently DSP and concentrations of dissolved P in ground water because of the preferential flow characteristics in the Hula Valley's semiarid wetland in Israel. This effect occurs due to localised accumulations of P, which in turn are because of the existence of preferential flows, leading to a form of by-pass P transport in soils in which P would normally be expected to be sorbed (Van der Zee and van Riemsdijk, 1988). Several studies tried to relate short term soil P tests to long term soil P behaviour for sandy and acidic soils. These phenomena are very difficult to predict and therefore to model because soil is a heterogeneous matter with

⁷ Olsen-P represent the readily available P in soil, it is measured by extracting P with sodium bicarbonate after Olsen methods (Olsen, 1954)

anisotropic properties. Nevertheless, the amount of P a soil can adsorb is finite and with an N-based nutrient management, P introduced by fertilisation with biosolids or manure annually would exceed crop requirements and therefore, the “year” time scale might not be appropriate to limit risk of P leaching. (Maguire et al., 2008) studied soil test P and crop yield on a long term field trial on high soil P fertilised with poultry litter or inorganic P. Maguire et al observed a reduction in soil P test over a few years when nutrient management was changed without a decrease in yields.

Zou et al. (1992) measured rates of P gross mineralisation and immobilisation. They found them ranging from 0.6–3.8 and 0–4.3 mg.kg⁻¹ of soil per day, respectively, for the four soils; Alfisol, Mollisol, Ultisol and Andisol. On considering an average bulk density for Andisol (clay loam) of 700 kg.m⁻³ (Prado et al., 2006) a maximum of 11 kg.ha⁻¹.yr⁻¹ can be calculated based on this data. However, (Zou et al., 1992) pointed out the lack of study on these P processes explained by the lack of analytical method. Especially for P, time dependent processes are significant (McGechan, 2002) with significant eutrophic P coming from slow and time-dependent reactions.

P processes are difficult to model because equilibrium between P in solution and P adsorbed results from slow, reversible and fast processes (Lewis and McGechan, 2002). A P based nutrient management can reduce soil P test significantly, and also as Fraser et al. (2004) suggested, plant development and nutrient uptake evolution consideration for fertiliser application would limit risks of P leaching. Hence, as the relationship between laboratory determined soil P maximum sorption capacity and prediction of P leaching is difficult to establish (Falkiner and Polglase, 1997), a P based nutrient management to establish irrigation rate in a WaterRenew system would limit risk of leaching.

Another process to take into account and that is difficult to predict concerns the consequences of the interactions and combinations of the different ions brought by irrigation on soil characteristics. McGechan (2002) makes it clear that irrigation with saline wastewater to incorporate Na compounds into clay will cause a release of P as Na will replace them. Sharpley et al. (1988) had also reported increased P solubilisation when soil is saturated with Na.

There were specific studies on P leaching when high doses of P were applied on soil as biosolids, liquid digested sewage sludge (Shepherd and Withers, 2001) or also sludge cakes on lysimeters but not with sewage. Also a long term watershed scale study was conducted in Illinois where high loads of P ($530 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ for 31 years) were applied as biosolids on fields and surface water quality monitored. (Tian et al., 2006) found significant increase in surface water TP concentrations, especially during summer and fall, but only from $0.10 \text{ mg} \cdot \text{L}^{-1}$ to $0.16 \text{ mg} \cdot \text{L}^{-1}$ and therefore under legal consent. Tian concluded that even high loads of nutrients for a long period had minor impact on surface water quality.

3. Processes involving potassium potentially presenting an environmental risk

K can leave the soil compartment when soluble as K^+ (Rowell, 1994). However, K leaching does not represent any environmental risks and won't be discussed further.

2.3 CONCLUSION

In this section, it was underlined first that the nutrients composition of urban wastewater was matching woody energy crops nutrients requirement. This was true for willow, but for eucalyptus and poplar, urban wastewater is too high for P and too low for K.

Second, processes happening in soil involving enrichment or consumption of different N, P and K pools (organic, inorganic, soluble or particulate etc) have been identified and studied and available in an exhaustive literature and could be summarized in a conceptual model.

Third, it was explained that these different processes occurred at different time-scales for P and this could enhance risks of leaching or runoff of nutrients if not taken into account. One of the time-dependent processes being the capacity of nutrients uptake by plants, because related to season variable evapotranspiration rate. Moreover, plants are playing a major role in nutrients cycling, not only in terms of time-scale but also by influencing processes. For this reason, locally adapted trees are essential for phytoremediation success (Rockwood et al., 2004) and wastewater loading should be nutrients based rather than hydraulic based.

Finally, some processes, especially P related, need to be studied more (McGechan, 2002) and an integrating modelling tool needs to be developed (Zou et al, 1992). Such

a model could be an efficient tool to help managing, optimising and make safer wastewater irrigated energy crops production systems.

3. RISKS OF WASTEWATER IRRIGATION FOR CROP PRODUCTION TO SUSTAINABILITY: NON NUTRIENTS ASPECTS

In section 2, we discussed the risks associated to wastewater irrigation for SRC, with a focus on nutrients. In this section, we will focus on the other risks associated with such systems.

3.1 TREE STRESS MANAGEMENT CAPACITY

1. Resistance/ tolerance to some nutrients (especially micro nutrients and salts)

- Willow

Punshon and Dickinson (1999) investigated *Salix* sp. resistance to Cu, Cd, Ni and Zn.

Root elongation was used to determine resistance level and it was found to be important. Highest resistance was found in response to Cd, while Cu and Ni were extremely toxic. They found Cu concentration reached a maximum of 2,000, 400, and 82 $\mu\text{g.g}^{-1}$ (d.wt) in roots, wood, and foliage, respectively, after 1 month in hydroponic culture.

- Poplar

Timmer and Teng, (1990) reported poplars' hybrid sensitivity to phosphorus and P-induced micronutrients disorders. Two levels of Zn and Cu were tested as well. Plant growth and leaf health were affected. However, Zn and Cu alone didn't have a growth reduction effect. The results confirmed that excessive P fertilisation may induce Zn and Cu deficiency in nursery grown hybrid poplar. Negative effect of P application of 1,152 kg.ha^{-1} couldn't be compensated by Zn and Cu addition at the rate of 11.25 kg.ha^{-1} . even if it was compensated for P application rate of 576 kg.ha^{-1} .

- Eucalyptus

(Bhati and Singh, 2003) investigated Eucalyptus (*E.camaldulensis*) seedlings' resistance to different kind of effluents; steel, textile and municipal, alone or mixed. High concentrations of metal ions and low concentrations of Ca, Mg, K, Na, N and P in soil resulted in high mortality of seedlings within a few days. Concentrations of Cu, Fe,

Mn and Zn were over 10^4 times higher in steel effluent than in their reference sample of good water (Cu 0.003 mg.L^{-1} vs. 91 mg.L^{-1} , Fe 0.08 mg.L^{-1} vs. 320 mg.L^{-1} , Mn 0.022 mg.L^{-1} vs. 280 mg.L^{-1} , Zn 0.017 mg.L^{-1} vs. 375 mg.L^{-1}). High concentration of Na might reduce Mg and micronutrient concentration in seedlings potentially affecting root and leaf growth. Hence, *E.camaldulensis* seedlings show quite low sensitivity to micronutrients concentrations.

- Conclusion

The relatively low sensitivities of poplar, willow and eucalyptus to micronutrients concentrations make them suitable to be irrigated by different source of effluents.

2. Water stress/ roots anoxia

Paranychanakis et al (2006) report woody crops resistance to flooding. Depending on the hybrid, tolerance to flooding is different but Eucalyptus sp, Willow sp, and Poplars sp are tolerant to flooding.

Kozłowski and Pallardy (1997) underline the fact that the timing at which flooding takes place during the season has a significant impact as even flood-tolerant plants can be adversely affected by flooding during their development stage and on the other hand, non-tolerant plants during dormant season won't be harmed if the flooding is short.

Hence, a good adaptation of irrigation rate has to be performed to prevent adverse effects of over irrigation.

3.2 PUBLIC HEALTH RISKS BECAUSE OF PRESENCE OF PATHOGENS IN WASTEWATER

The World Health Organization (WHO, 2006) produced guidelines for wastewater reuse in agriculture in order to protect people eventually in contact with wastewater. WHO appoints wastewater treatments adapted to different type of crops (food, non-food) in order to reach the necessary microbiological state and limit risks of contamination. Indeed, risks are lower for energy crops than for food crops. Pathogenic contamination could happen by direct contact with wastewater, by inhalation or ingestion of contaminated food, or by indirect contact by contamination of drinking water. Thus, wastewater can be a resource but it also can be a source of infectious agents and chemicals, thereby presenting a risk for public health. In this guideline, wastewater use in agriculture was assessed using the Stockholm framework, an integrated approach combining risk assessment and risk management

to control water related diseases.

A summary table of recommended microbiological quality guidelines for treated wastewater used for crops irrigation is available in this guideline (WHO, 2006) and according to this table, treatments required are sedimentation and stabilisation in ponds (Table 6). Because of their size (*E.coli* cell diameter range is 1-6 μm), bacteria and parasites got efficiently filtered out in a soil. Hekman et al., (1995) found the finer the soil texture, i.e. with increasing clay content, the more bacterial straining increases in undisturbed soil columns. But Mosaddeghi et al., (2009) observed the possibility of bypass flow pathway developing in the soil profile, especially under well structured soil. Indeed, Mosaddeghi et al compared the effect of different types of bacterial sources (poultry litter, manure, sewage) and soil type on bacterial contamination of water leaching out of undisturbed soil columns and observed that type of waste may influence more the risk for microbial contamination of aquifers. On the irrigation side, as WaterRenew systems consider only non-food crops, the only specification is not to use sprinklers as it would spray eventual pathogens present in the irrigation water and eventually contaminate workers by inhalation.

Carlander et al. (2000) investigated transport and retention of bacteriophages in two types of willow-cropped lysimeters. The concern was raised as viruses are much smaller than bacteria and can be harmful from very little concentration. Two types of soil were also investigated during this work, clay and sand. They found that sand soil slowed bacteriophages transport more than clay soil and also sand soil retention capacity was much greater than clay but clay soil retention capacity was still fairly high. Willow plants, especially roots development do not facilitate virus transport through the soil. Carlander calls for precaution not to allocate wastewater irrigation in vulnerable areas, such as areas where water is extracted for drinking water.

WHO (Aertgeerts et al., 2003) compiled in *Health risks in aquifer recharge using reclaimed water - State of the art report* (2003) information about distance transported of viruses (vertical and horizontal) in different kinds of soils by location on different continents. Wastewater used ranges from raw effluent to tertiary treated wastewater (Yates and Gerba, 1998). Transportation of viruses varies from 50 cm till 29 m depth for two types of sandy soil and secondary treated effluent.

Another study on sandy soil also concluded that, wastewater irrigation had a positive effects on soil microbiological population in mass and in biological activities, even under long term irrigation (20 years) and no increase of *E.coli* or viruses could be

detected in ground waters under irrigation sites (Zdenek and Demnerova, 2007).

Table 5 Survival of various organisms in selected environmental media at 20-30 °C.
Source: WHO, 2006

<i>Organism</i>	<i>Survival times (days)</i>		
	Fresh water and sewage	Crops	Soil
Viruses			
Enteroviruses	<120, usually <50	<60, usually <15	<100, usually <20
Bacteria			
Thermotolerant coliforms	<60, usually <30	<30, usually <15	<70, usually <20
Salmonella spp.	<60, usually <30	<30, usually <15	<70, usually <20
Shigella spp.	<30, usually <10	<10, usually <5	ND
V. cholerae	ND	<5, usually <2	<20, usually <10
Protozoa			
E.histolytica cysts	<30, usually <15	<10, usually <2	<20, usually <10
Cryptosporidium oocysts	<180, usually <70	<3, usually <2	<150, usually <75
Helminths			
Ascaris eggs	Years	<60, usually <30	Years
Tapeworm eggs	Many months	<60, usually <30	Many months

ND, no data, Sources: WHO 2006 volume 2, chapter 5.

Conclusion

Bacteria and parasites are well removed by sedimentation and also well filtered by soil in general. In the specific case of energy crops, public exposure to pathogens is limited and the workers are the only ones required to take safety measures. Despite their size and potential for harm to health, viruses are fairly well retained in soil and willow presence doesn't facilitate their transport.

3.3 RISK OF ACCUMULATION OF HEAVY METAL OR HAZARDOUS MATERIAL THAT WILL BE STORED IN THE TREES AND RELEASED WHEN BURN OR ACCUMULATION OF HEAVY METALS IN SOIL

3.3.1 Heavy metals in wastewater and risk of accumulation of heavy metals in soil

Heavy metals (Cadmium, Cd, Copper, Cu, Chrome, Cr, Mercury, Hg, Nickel, Ni, Lead, Pb, and Zinc, Zn) are present generally only in industrial wastewater (Lin and Banin, 2006) and are quite negligible in municipal wastewater (Paranychianakis et al 2006). Their discharge is regulated by the formerly named Directive (76/464/EEC) for discharges of certain dangerous substances, now codified 2006/11/EC. Thanks to their implementation since the 60's, the median concentrations of Zn, Cu and Cr have decreased by 20-30 % from 1988; Ni content has declined by nearly 40 % and Pb by about 50 %. Then, concerns are more focused on control of diffuse pollution sources of heavy metals (Smith and CAB International, 1996).

Concerns and precautions are needed when sewage sludge (dewatered or not) is used for fertilisation. Indeed, according to ADEME (1995) on the fate of metals during wastewater treatment, only 10 to 30 % of metallic micropollutants end up in the effluent, whereas, 70 to 90 % end up in sludge (cf. Figure 5).

Once applied to soil in sewage sludge, heavy metals are retained indefinitely in the cultivated layers (McGrath and Lane, 1989). (Smith and CAB International, 1996) calculated the minimum number of years to reach the maximum soil limit for the most limiting heavy metal (EC, 1986). He concluded the minimum would be 18 years and this was for Hg. Those numbers are given for sewage sludge containing 90 % of the heavy metals, and for this reason, in theory, for treated effluent application, this minimum period could be 162 years. This validates the fact that wastewater supply in heavy metal is negligible in term of soil accumulation.

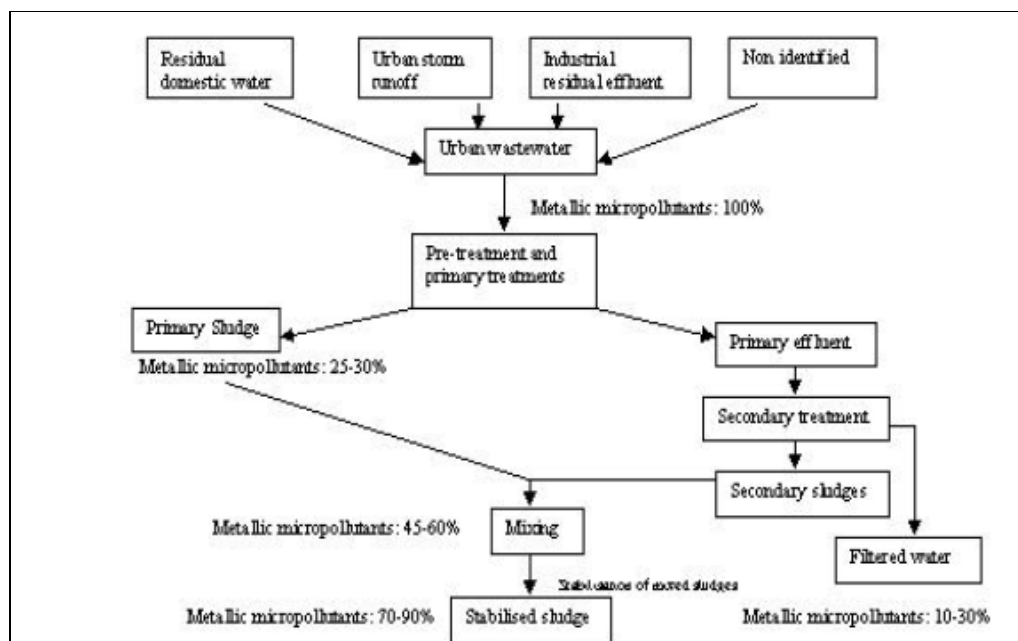


Figure 4 Origin and fate of metals during treatment of wastewater, from ADEME 1995, source: ICON, 2001

Moreover, Metcalf and Eddy (1991), Siebe and Fischer (1996) and AATSE (2004) conducted long terms field studies of irrigation with treated or untreated wastewater. The Metcalf et al (1991) study was conducted over 76 years of irrigation with treated wastewater in Australia and no significant increase in Cd in soil or plant was measured. Then Siebe et al (1996) reported a significant increase in heavy metals in soil and not plants after irrigation with wastewater for more than 80 years in Mexico. However, the concentrations resulting from accumulation of heavy metals remained under international consents for soil. Finally, AATSE (2004) reported a significant accumulation of Pb and Cu in the first 15 cm of a soil irrigated with domestic wastewater in India for 35 years. But for Zn, Co, Cr, Mn and Pb and Cu, heavy metals' concentrations in soil remained under EU maximum limit levels.

Therefore the risk of accumulation of heavy metals in soil subsequent to domestic wastewater application, even on the long term, is very low.

3.3.2 Accumulation of heavy metals in plants and effect on yields

In the previous section, heavy metal accumulation in soil after wastewater irrigation was found to be negligible. In the event that heavy metal does accumulate in soil, such WaterRenew system would not be sustainable and should not be carried on, however,

what would happen on the tree and on the SRC point of view if heavy metals do accumulate in soil? What can be the risks associated?

Poplars, willows and eucalypts are non-hyper-accumulating species (Rockwood et al., 2004) i.e., relatively low contaminant concentrating and for this reason, because of their high biomass productivity, they may phytoremediate and produce fuel wood and other timber products to generate revenue without exporting contaminant in their biomass.

However, they are quite tolerant and can grow without significant loss in yield in contaminated soil. (Salix, Landberg and Greger, (1996), Salix and Populus, Fischerova et al. (2006), Eucalyptus, Arriagada et al. (2006))

Thus, heavy metals present in soil can be concentrated in soil or uptaken by the trees. In the case of uptake and concentration in tree biomass, what are their fates when the trees are burnt?

- Poplar sp.

Poplars' trials irrigated and fertilised with sludge (Moffat et al., 2001/3) suggested that for heavy metals other than Cadmium (Cd), poplar SRC treated with sewage sludge will lead to heavy metal accumulation in the soil. Even for Cd, Moffat et al (2001) underlines that it would be unreasonable to propose poplar as a Cd phytoremediation candidate. For these reasons, for poplar, heavy metals released from wood will not be problematic as poplar doesn't uptake them significantly.

- Willow sp.

Willow has been identified as Cd remover (Landberg and Greger, 1996; Dimitriou et al., 2006). But willow is not a non-hyper accumulator, and therefore the amount of Cd exported remains low. To avoid heavy metals' accumulation in soil, they should be applied only in proportion such that willow can uptake them (Hasselgren, 1999).

- Eucalyptus sp.

Arriadaga et al (2006) identified symbiotic association between fungi and eucalyptus' roots that increased Eucalyptus sp.' tolerance to heavy metal and also growth rate. However, Cd uptake ability of Eucalyptus in symbiosis remained under the ability of hyper-accumulators.

- Conclusion

The uptake of heavy metals by SRC does not appear to be significant enough to fear significant bioaccumulation in their tissues (Hasselgren, 1999, Rockwood et al, 2004, Arriadaga, 2006). So there is a low risk in term of heavy metal release by combustion of crops irrigated by wastewater. However, because of their limited ability to uptake them, heavy metals will accumulate in the soil if metaliferous industrial wastewaters are used for irrigation. Hasselgren (1999) reports that this accumulation occurs in the top soil layer where heavy metals seem to be fixed in the organic soil and prevented to leach into groundwater. However, soil accumulation, if happening, should be maintained under toxic levels for SRC or other crops grown later in the same location (Hasselgren, 1999). In case sewage sludge (dewatered or not) is applied to energy crops, then, their heavy metal concentrations are not negligible and because of their high biomass productivity, the proportion of heavy metals in ashes of these energy crops after combustion could be problematic. However, technological solutions exist (Oberberger et al, 1997, Vervaeke et al, 2005) and heavy metal recoveries in ashes are efficient and the part not recovered remains low compared to the emission limits (Vervaeke et al, 2005).

3.4 RISK OF INCREASED ATMOSPHERIC EMISSION OF GREENHOUSE EFFECT GAS BY DENITRIFICATION OF WASTE NITRATE APPLIED ON SOIL

Nitrous oxide is a greenhouse gas and can be produced by denitrification. Nitrous oxide production has to be limited and therefore, the following risk needs to be taken into account (Li et al, 2005). So far, denitrification is typically assessed as the missing part of N after calculating N balance (Dimitriou and Aronsson, 2004) and not measured. However, several studies reveal that denitrification might be happening mainly during a short period after N application and would drop fast afterwards (Marshall et al., January 2001). (Liu et al., 2007) reassessed the importance of denitrification in N-cycle and conclude that denitrification proportion was much closer to 1 % with an upper limit of 10 % of total N in the system. And this even in condition of great NO_3^- supply.

However, all these studies are based on limited N application. In the case of fertigation, the option to irrigate trees all year long is considered. In that case, will denitrification's role in N cycle remains low?

3.5 RISK OF SOIL SALINISATION

Patterson (1996) reported water soluble salts, in particular Na concentrations in domestic wastewater not diminishing after primary, secondary or tertiary treatments. When irrigation is conducted with water containing high concentration of soluble salts, there is risk of accumulation of salts where the water will percolate. This accumulation becomes problematic when it occurs around the root zone. With salt concentrations increasing in soil solution, plants will have more and more difficulty extracting enough water. Then, according to salt tolerance of the crop grown, yield will reduce (Westcot et al., 1985.). Accumulation of water soluble salts in soil is defined as salinisation of soil (Richards and Allison, 1954.). It has heavy consequences on soil structures: a loss of soil structure by swelling and dispersion of soil clay leading to a decrease of hydraulic conductivity (Rowell, 1994). If the major soluble salt is Na, then we observe sodicification. If this is accompanied with increase in pH, then we observe alkalinisation (Richards and Allison, 1954.).

Ayers and Westcot (Westcot et al., 1985.) recommend then to irrigate more than the crop requirement in order to leach salts under crop root zones (LR, leach requirement). Leaching is according to them “the key to controlling a water quality-related salinity problem”. However, the problem in a WaterRenew system is that if leaching is provoked, then, not only soluble salts but also nutrients or pathogens in solution might then be leached as well (Letey, c2007.).

Therefore, if in a WaterRenew system, water with high content in soluble salts (cf. guidelines in FAO 29 to determine effluent quality prior to irrigation); there will be a real risk of soil salinisation. Therefore, effluent should be treated until it presents appropriate quality for irrigation.

3.6 RISK ON RIVER AND GENERAL HYDROLOGY

According to the Environment Agency, in England and Wales, over 10 billion litres of wastewater are collected and disposed into surface water every day using over 350,000 km of sewers and 6,000 discharges from sewage treatment works and 25,000 intermittent discharges.

Because of these figures, especially in summer, wastewater discharge can be a major part of surface water supply in terms of volume. Therefore, redirecting the totality or a significant proportion of these discharges to irrigation for SRC within a WaterRenew system might cause a deficit of flow in certain rivers especially in summer.

But in a WaterRenew system, water applied and not used by the crops will percolate in the soil matrix and reach groundwater and then potentially contribute to artificial aquifer recharge, an interesting option for semi-arid or arid zones to prevent quality decrease in aquifers water (OAS et al., 1997; Gale, 2005).

- Willow

However, in the UK, (Stephens et al., 2001a; Stephens et al., 2001b) outlines the risk of decrease of national freshwater resources in the driest part of the UK if energy crops were introduced to replace economically less interesting arable crops. They found that energy crops with deep roots might reduce significantly water percolation beyond the root zone during the growing season and even dry it so much that soil moisture might not be refilled during the winter rainfall, hence creating a deficit on the annual water balance. The reduction in hydrologically efficient rainfall can represent as much as 90 % on replacing wheat by willow and on the national scale, the reduction of the total freshwater resource can raise to an equivalent of 0.2 % of the national freshwater resource or 12 % of annual freshwater abstractions.

- Poplar

Lyons et al. (2001) evaluated poplar cultivation on SRC on water resources in England and Wales. They get to the same conclusions as Stephens et al (2001), i.e. increased poplar planting would be unsustainable in Anglia region, unless other water users' water needs are curtailed.

However, these studies take into account water balance without considering water reuse. In the case of SRC of poplar or willow irrigated with wastewater, how would the water balance be affected? For some surface waters, wastewater effluent represents a significant flow of their flux, especially in summer. As Stephens et al (2001) and Lyons et al (2001) advise it, before introducing SRC energy crops on arable lands, a proper impact study has to be performed.

4. CONCLUSION

The system "SRWC treating wastewater" is an efficient system. Except for the establishment year, where mineralisation is high, N loads that can be treated by SRWC are much higher than the crop requirements and with assumption that willow is not a P-hyperaccumulator ($\leq 1\%$ P in the dry matter), the system is suitable for wastewater treatment. Indeed, there is a good match between nutrient composition of

secondary treated wastewater and SRC (willow, poplar and eucalyptus) nutrient requirements and risks associated with comparable technology (fertilisation with poultry litter, animal manure, sewage sludge) identified from the literature were limited. The exhaustive literature on N and P dynamics in soil revealed first for both N and P that a good nutrient management reduces efficiently leaching risks. Second, for N, denitrification risks of nitrates into greenhouse gas N_2O is greatly increased by high soil moisture, though not quantified. Third, usually P is brought in excess when nutrient management is based on N loads. As soil presents a P sorption capacity, it is usually not a problem, however this sorption capacity is finite and can threaten the system sustainability. Regarding heavy metals, as effluent contains very low concentrations, they were reported as not being a major concern either for soil or crops. Pathogens' contaminations were also reported as not a major concern as long as wastewater was treated following guidelines developed for each specific use (food crops, energy crops). On the hydrological point of view, the impact of both diverting flow from surface water and increasing ET loss by planting SRC have to be assessed by conducting a proper impact assessment for installing a WaterRenew system.

Research reported in the literature never managed to "crash" the systems studied and therefore upper limit for maximum sustainable N and P applications and irrigation rate still needs to be quantified. The gaps in knowledge identified from this literature review are:

- Treatment efficiency for P of SRC of willow, poplar and eucalyptus for different application rates and for different type of soils.
- Test leaching behaviour for P as it has been done for Nitrogen (effect of application rate, effect of soil etc) for willow, poplar and eucalyptus.
- All Nitrogen leaching, removal or uptake measurements were done on lysimeter trials and not on field scale (Aronsson et al, 2000)
- Close N cycle on SRC irrigated with wastewater, measurement of gaseous denitrification products, quantification of nitrous oxide produce as one of the greenhouse effect gas. (can put at stake the entire sustainability of WaterRenew system)
- Modelling of nutrients fate, from wastewater into wherever in WaterRenew system (uptaken by trees or removed or leached), able to take into account site specificities

- Need of a practical tool to design and plan the management and implementation of the system.

5. RESEARCH AIM AND OBJECTIVES

The aim of the research (Chapter 1) is to contribute to the further understanding of soil-vegetated based wastewater system. This in order to identify the necessary and sufficient factors (principally among climatic, edaphic, plant, effluent characteristics) to be taken into account to calculate its minimum size to optimise both efficient nutrients removal from wastewater and yield for SRC.

Therefore, a field trial was set up at Cranfield University sewage treatment work where *Salix viminalis*, *Populus trichocarpa* and *Eucalyptus gunnii* trees were planted to be irrigated with secondary treated effluent from the work.

In order to achieve this research aim, objectives are formulated in relationship with the field trial set up at Cranfield University sewage treatment work:

Knowledge oriented objective which can be subdivided in other objectives: Understanding and quantifying processes in nutrients removal in WR system and optimisation

- To improve wastewater treatment process understanding by soil and plant. To quantify the main treatment processes and assess the relative importance of each compartment (the field trial will provide these information)
- To describe the temporal dynamics of P and N (establishment year, seasonal effect) with an emphasis on P accumulation processes as they are time-dependent and have been less studied and understood (field and supporting experiments will be necessary)

Practical tool development objective which can be subdivided into other objectives: Development of a model to assess feasibility and sustainability

- Development of a model as a useful process for conceptualisation of this environmental system.
- Recommendation for design and operation on field system.

6. REFERENCES

- AATSE (2004), "Water recycling in Australia.", *Melbourne, Australian Academy of Technological Sciences and Engineering, cited in WHO guidelines for the safe use of wastewater, excreta and greywater (2006)*, .
- Aertgeerts, R., Angelakis, A. and World Health Organization (2003), *State of the Art Report Health Risks in Aquifer Recharge Using Reclaimed Water-Restricted English only*, SDE/WSH/03.08.
- Alker, G. R., Godley, A. R. and Hallett, J. E. (2003), "Landfill leachate management by application to short rotation willow coppice.", *Ninth International Waste Management and Landfill Symposium*, .
- Armstrong, A., Johns, C. and Tubby, I. (1999), "Effects of spacing and cutting cycle on the yield of poplar grown as an energy crop", *Biomass and Bioenergy*, vol. 17, no. 4, pp. 305-314.
- Aronsson, P. and Perttu, K. (2001), "Willow vegetation filters for wastewater treatment and soil remediation combined with biomass production.", *Forestry Chronicle*, vol. 77, no. 2, pp. 293-299.
- Aronsson, P. G. and Bergstrom, L. F. (2001), "Nitrate leaching from lysimeter-grown short-rotation willow coppice in relation to N-application, irrigation and soil type", *Biomass and Bioenergy*, vol. 21, no. 3, pp. 155-164.
- Aronsson, P. G., Bergstrom, L. F. and Elowson, S. N. E. (2000), "Long-term influence of intensively cultured short-rotation Willow Coppice on nitrogen concentrations in groundwater", *Journal of Environmental Management*, vol. 58, no. 2, pp. 135-145.
- Arriagada, C. A., Herrera, M. A. and Ocampo, J. A. (2006), "Beneficial effect of saprobe and arbuscular mycorrhizal fungi on growth of Eucalyptus globulus co-cultured with Glycine max in soil contaminated with heavy metals", *Journal of Environmental Management*, vol. In Press, Corrected Proof.
- Berg, U., Donnert, D., Ehbrecht, A., Bumiller, W., Kusche, I., Weidler, P. G. and Nuesch, R. (2005), ""Active filtration" for the elimination and recovery of phosphorus from waste water", *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 265, no. 1-3, pp. 141-148.
- BERR (2008), "UK renewable energy strategy: consultation document", *Departement of Buisiness, Enterprise and Regulatory Reform*, .
- BERR, DEfRA and DIUS (2008), "UK environmental transformation fund: strategy, URN 08/827", .
- Bhati, M. and Singh, G. (2003), "Growth and mineral accumulation in Eucalyptus camaldulensis seedlings irrigated with mixed industrial effluents", *Bioresource Technology*, vol. 88, no. 3, pp. 221-228.
- Brady, N. C. and Weil, R. R. (eds.) (2001), *The Nature and Properties of Soils*. Prentice Hall, New York.
- Bullard, M. J., Mustill, S. J., McMillan, S. D., Nixon, P. M. I., Carver, P. and P. Britt, C. (2002), "Yield improvements through modification of planting density and harvest

- frequency in short rotation coppice *Salix* spp.—1. Yield response in two morphologically diverse varieties", *Biomass and Bioenergy*, vol. 22, no. 1, pp. 15-25.
- Cai, Z., Laughlin, R. J. and Stevens, R. J. (2001), "Nitrous oxide and dinitrogen emissions from soil under different water regimes and straw amendment", *Chemosphere*, vol. 42, no. 2, pp. 113-121.
- Carlander, A., Aronsson, P., Allestam, G., Stenström, T. A. and Perttu, K. (2000), "Transport and retention of bacteriophages in two types of willow-cropped lysimeters.", *Journal of Environmental Science and Health, Part A*, vol. 35, no. 8, pp. 1477-1492.
- DECC (2008), "Ministerial responsibilities at the Department of Energy and Climate Change", *DEPARTMENT OF ENERGY AND CLIMATE CHANGE News Release*, vol. Ref: 2008/2.
- DEFRA (2002.a), *Growing short rotation coppice : best practice guidelines for applicants to DEFRA's energy crops scheme*. DEFRA, London.
- DEFRA (2002.b), *Sewage treatment in the UK : UK implementation of the EC Urban Waste Water Treatment Directive : sensitive areas : September 2002*, Department for Environment, Food & Rural Affairs, London.
- DEFRA (2002a), "Guidelines for Farmers in NVZs – England.", vol. PB5505.
- DEFRA (2002b), *Implementation of the Nitrates Directive (91/676/EEC), Description of the methodology applied by the Secretary of State in identifying additional Nitrate Vulnerable Zones in England*. Water Quality Division, 1.
- Dickmann, D. I., Isebrands, J. G., Eckenwalder, J. E. and Richardson, J. (. (2001), "Poplar Culture in North America.", , pp. 395.
- Dimitriou, I. and Aronsson, P. (2004), "Nitrogen leaching from short-rotation willow coppice after intensive irrigation with wastewater", *Biomass and Bioenergy*, vol. 26, no. 5, pp. 433-441.
- Dimitriou, I., Eriksson, J., Adler, A., Aronsson, P. and Verwijst, T. (2006), "Fate of heavy metals after application of sewage sludge and wood-ash mixtures to short-rotation willow coppice", *Environmental Pollution*, vol. 142, no. 1, pp. 160-169.
- EC (23/01/2008), "Proposal for a directive of the European parliament and the council on the promotion of the use of energy from renewable sources", *2008/0016 (COD)*, .
- EC (2000.), *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy*. Office for Official Publications of the European Communities, Luxembourg.
- EC (1991), *Council Directive 1991/676/EEC of the Council of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources*. Office for Official Publications of the European Communities, Luxembourg.

- EC (1986), "Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture.", *86/278/EEC*, .
- Evans, J. (1983), "Notes on growing Eucalyptus in Britain.", *Forestry Commission Booklet 50.*, , pp. 31.
- Falkiner, R. A. and Polglase, P. J. (1997), "Transport of phosphorus through soil in an effluent-irrigated tree plantation.", *Australian Journal of Soil Research*, vol. 35, no. 2, pp. 385-398.
- Falkiner, R. A. and Polglase, P. J. (1999), "Fate of applied phosphorus in an effluent-irrigated *Pinus radiata* plantation.", *Australian Journal of Soil Research*, vol. 37, no. 6, pp. 1095-1106.
- FAO (1985), *Guidelines: Land Evaluation for Irrigated Agriculture*. 55, FAO Soils Bulletin, FAO, Rome.
- Fischerova, Z., Tlustos, P., Jirina Szakova, and Kornelie Sichorova, (2006/11), "A comparison of phytoremediation capability of selected plant species for given trace elements", *Environmental Pollution*, vol. 144, no. 1, pp. 93-100.
- Fraser, L. H., Carty, S. M. and Steer, D. (2004), "A test of four plant species to reduce total nitrogen and total phosphorus from soil leachate in subsurface wetland microcosms", *Bioresource Technology*, vol. 94, no. 2, pp. 185-192.
- Gale, I. (2005), *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas*. UNEP/DTIE/IETC , UNESCO–IAH information booklet, UNESCO–IAH information booklet.
- GB, Parliament. Joint Committee on Statutory Instruments. (2008), *The nitrate pollution prevention regulations 2008.(SI 2008/2349)*, The Stationery Office.
- Hammer, M. J. and Hammer, M. J. (2008.), *Water and wastewater technology*, 6th ed, Pearson Prentice Hall ; Pearson Education, Upper Saddle River, N.J. : London.
- Hasselgren, K. (1999), "Utilization of sewage sludge in short - rotation energy forestry: a pilot study", *Waste Management and Research*, vol. 17, no. 4, pp. 251-262.
- Heckrath, G., Brookes, P. C., Poulton, P. R. and Goulding, K. W. T. (1995), "Phosphorus Leaching from Soils Containing Different Phosphorus Concentrations in the Broadbalk Experiment", *Journal of Environmental Quality*, vol. 24, no. 5, pp. 904-910.
- Hekman, W. E., Heijnen, C. E., Burgers, S. L. G. E., van Veen, J. A. and van Elsas, J. D. (1995), "Transport of bacterial inoculants through intact cores of two different soils as affected by water percolation and the presence of wheat plants. 1995;16:143–158", *FEMS Microbiol Ecol.*, vol. 16, pp. 143-158.
- Jarvie, H. P., Neal, C., Williams, R. J., Neal, M., Wickham, H. D., Hill, L. K., Wade, A. J., Warwick, A. and White, J. (2002), "Phosphorus sources, speciation and dynamics in the lowland eutrophic River Kennet, UK", *The Science of The Total Environment*, vol. 282-283, pp. 175-203.
- Kozlowski, T. T. and Pallardy, S. G. (1997), "Growth Control in Woody Plants.", .

- Kundu, B. S. and Gaur, A. C. (1980), "Establishment of nitrogen-fixing and phosphate-solubilising bacteria in rhizosphere and their effect on yield and nutrient uptake of wheat crop", *Plant and Soil*, vol. 57, no. 2, pp. 223-230.
- Landberg, T. and Greger, M. (1996), "Differences in uptake and tolerance to heavy metals in *Salix* from unpolluted and polluted areas", *Applied Geochemistry*, vol. 11, no. 1-2, pp. 175-180.
- Letey, J. (c2007.), "Guidelines for Irrigation Management of Saline Waters are Overly Conservative", in *Wastewater reuse - risk assessment, decision-making and environmental security*, Zaidi, Mohammed K.; NATO ed, Springer, Dordrecht ; [London], pp. 205-218.
- Lewis, D. R. and McGechan, M. B. (2002), "SW--Soil and Water: A Review of Field Scale Phosphorus Dynamics Models", *Biosystems Engineering*, vol. 82, no. 4, pp. 359-380.
- Licht, L. A. and Isebrands, J. G. (2005), "Linking phytoremediated pollutant removal to biomass economic opportunities", *Biomass and Bioenergy*, vol. 28, no. 2, pp. 203-218.
- Lin, C. and Banin, A. (2006), "Phosphorous retardation and breakthrough into well water in a soil-aquifer treatment (SAT) system used for large-scale wastewater reclamation", *Water Research*, vol. 40, no. 8, pp. 1507-1518.
- Litaor, M. I., Reichmann, O., Belzer, M., Auerswald, K., Nishri, A. and Shenker, M. (2003), "Spatial Analysis of Phosphorus Sorption Capacity in a Semiarid Altered Wetland", *J Environ Qual*, vol. 32, no. 1, pp. 335-343.
- Liu, S. C., Cicerone, R. J. and Donahue, T. M. (1977), "Sources and sinks of atmospheric N₂O and the possible ozone reduction due to industrial fixed nitrogen fertilizers.", *Tellus*, vol. 29, pp. 251-263.
- Liu, X. J., Mosier, A. R., Halvorson, A. D., Reule, C. A. and Zhang, F. S. (2007), "Dinitrogen and N₂O emissions in arable soils: Effect of tillage, N source and soil moisture", *Soil Biology and Biochemistry*, vol. 39, no. 9, pp. 2362-2370.
- Lyons, H. A., Anthony, S. G. and Johnson, P. A. (2001), "Impacts of increased poplar cultivation on water resources in England and Wales", *Asp. Appl. Biol.*, vol. 65, pp. 83-89.
- MAFF, (2000), *Fertiliser recommendations for agricultural and horticultural crops (RB209)*, Seventh edition ed., the stationary office, London, UK.
- Maguire, R. O., Mullins, G. L. and Brosius, M. (2008), "Evaluating Long-Term Nitrogen-versus Phosphorus-Based Nutrient Management of Poultry Litter", *J Environ Qual*, vol. 37, no. 5, pp. 1810-1816.
- Mander, U., Kull, A., Kuusemets, V. and Tamm, T. (2000), "Nutrient runoff dynamics in a rural catchment: Influence of land-use changes, climatic fluctuations and ecotechnological measures", *Ecological Engineering*, vol. 14, no. 4, pp. 405-417.
- Marshall, S. B., Mullen, B. M., Cabrera, L. M., Wesley Wood, C., Braun, C. L. and Guerta, A. E. (January 2001), "Nitrogen budget for fescue pastures fertilized with

- broiler litter in Major Land Resource Areas of the southeastern US", *Nutrient Cycling in Agroecosystems*, vol. 59, pp. 75-83.
- Martin, P. J. and Stephens, W. (2006), "Willow growth in response to nutrients and moisture on a clay landfill cap soil. II: Water use", *Bioresource Technology*, vol. 97, no. 3, pp. 449-458.
- McGechan, M. B. (2002), "SW--Soil and Water: Sorption of Phosphorus by Soil, Part 2: Measurement Methods, Results and Model Parameter Values", *Biosystems Engineering*, vol. 82, no. 2, pp. 115-130.
- McGechan, M. B. and Lewis, D. R. (2002), "SW--Soil and Water: Sorption of Phosphorus by Soil, Part 1: Principles, Equations and Models", *Biosystems Engineering*, vol. 82, no. 1, pp. 1-24.
- McGrath, S. P. and Lane, P. W. (1989), "An explanation for the apparent losses of metals in a long-term field experiment with sewage sludge", *Environmental Pollution*, vol. 60, no. 3-4, pp. 235-256.
- Mengel, K. (1985), "Dynamics and Availability of Major Nutrients in Soils", in Stewart, B. A. (ed.) *Advances in Soil Science*, Springer-Verlag, NY, Berlin, Heidelberg, Tokyo, pp. 65-131.
- Metcalf and Eddy (1991), "Wastewater: treatment, reuse and disposal.", NY, McGraw-Hill, cited in *WHO guidelines for the safe use of wastewater, excreta and grey-water (2006)*, .
- Mitchell, C. P., Stevens, E. A. and Watters, M. P. (1999/8), "Short-rotation forestry - operations, productivity and costs based on experience gained in the UK", *Forest Ecology and Management*, vol. 121, no. 1-2, pp. 123-136.
- Moffat, A. J., Armstrong, A. T. and Ockleston, J. (2001/3), "The optimization of sewage sludge and effluent disposal on energy crops of short rotation hybrid poplar", *Biomass and Bioenergy*, vol. 20, no. 3, pp. 161-169.
- Montuelle, B., Kestemont, P. and Chalamet, A. (1992), "Kinetics of amino acids mineralization by a pond sediment bacterial community", *Hydrobiologia*, vol. 243-244, no. 1, pp. 71-77.
- Morris, J. D. and Collopy, J. J. (1999), "Water use and salt accumulation by *Eucalyptus camaldulensis* and *Casuarina cunninghamiana* on a site with shallow saline groundwater", *Agricultural Water Management*, vol. 39, no. 2-3, pp. 205-227.
- Mosaddeghi, M. R., Mahboubi, A. A., Zandsalimi, S. and Unc, A. (2009), "Influence of organic waste type and soil structure on the bacterial filtration rates in unsaturated intact soil columns", *Journal of Environmental Management*, vol. 90, no. 2, pp. 730-739.
- Neal, C., Jarvie, H. P., Neal, M., Love, A. J., Hill, L. and Wickham, H. (2005), "Water quality of treated sewage effluent in a rural area of the upper Thames Basin, southern England, and the impacts of such effluents on riverine phosphorus concentrations", *Journal of Hydrology*, vol. 304, no. 1-4, pp. 103-117.
- OAS, UNEP and IETC (1997), *Source Book of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean*, Unit of Sustainable Develop-

- ment and Environment General Secretariat, Organization of American States, Washington, D.C.
- Paranychianakis, N. V., Angelakis, A. N., Leverenz, H. and Tchobanoglous, G. (2006), "Treatment of Wastewater With Slow Rate Systems: A Review of Treatment Processes and Plant Functions", in *Critical Reviews in Environmental Science and Technology*. Boca Raton: 2006. Vol. 36, Iss. 3 and pg. 187, 7. p. (eds.) , pp. 187-260.
- Patterson, R. A. (1996), "Demonstration of effects of sodicity on soil hydraulic conductivity in Proceedings of conference on "Innovative Approaches to the On-site Management of Waste and Water". Held at Southern Cross University Lismore, 26th November 1996.", .
- Pautler, M. C. and Sims, J. T. (2000), "Relationships Between Soil Test Phosphorus, Soluble Phosphorus, and Phosphorus Saturation in Delaware Soils", *Soil Sci Soc Am J*, vol. 64, no. 2, pp. 765-773.
- Pescod, M. B. (1992.), *Wastewater treatment and use in agriculture*, Food and Agriculture Organization of the United Nations, Rome.
- Pierzynski, G. M. (2000), "*Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters* ", *Southern Cooperative Series Bulletin*, vol. 396, pp. 102.
- Prado, B., Duwig, C., Escudey, M. and Esteves, M. (2006), "Nitrate Sorption in a Mexican Allophanic Andisol using Intact and Packed Columns", *Communications in Soil Science and Plant Analysis*, vol. 37, no. 15-20, pp. 2911-2925.
- Punshon, T. and Dickinson, N. M. (1999), "Heavy metal resistance and accumulation characteristics in willows.", *Int. J. Phytoremediat.*, vol. 1, no. 4, pp. 361-385.
- Purse, J. G. and Richardson, K. F. (2001), "Short rotation single stem tree crops for energy in the UK—an examination with Eucalyptus.13", *In: M.J. Bullard, Editor, Biomass and energy crops*, Association of Applied Biologists, York, UK, , pp. 13-20.
- Richards, L. A. and Allison, L. E. (1954.), *Diagnosis and improvement of saline and alkali soils*, U.S. Government Printing Office, Washington, D.C.
- Rockwood, D. L., Naidu, C. V., Carter, D. r., Rahmani, M., Spriggs, T. A., Lin, C., Alker, G. R., Isebrands, J. G. and Segrest, S. A. (2004), "Short-rotation woody crops and phytoremediation: Opportunities for agroforestry?", *Agroforestry Systems*, vol. 61-62, no. 1, pp. 51-63.
- Rosenqvist, H. and Dawson, M. (2005a), "Economics of using wastewater irrigation of willow in Northern Ireland", *Biomass and Bioenergy*, vol. 29, no. 2, pp. 83-92.
- Rosenqvist, H. and Dawson, M. (2005b), "Economics of using wastewater irrigation of willow in Northern Ireland", *Biomass and Bioenergy*, vol. 29, no. 2, pp. 83-92.
- Rosenqvist, H. and Dawson, M. (2005c), "Economics of willow growing in Northern Ireland", *Biomass and Bioenergy*, vol. 28, no. 1, pp. 7-14.
- Rowell, D. L. (1994), *Soil science : methods and applications*, Longman Scientific & Technical, Harlow.

- Sahrawat, K. L. and Keeney, D. R. (1986), "Nitrous Oxide Emission from Soils", in Stewart, B. A. (ed.) *Advances in Soil Science*, Springer-Verlag, NY, Berlin, Heidelberg, Tokyo, pp. 103-148.
- Scott, C. A., Zarazúa, A. J. and Levine, G. (2000), "Urban-Wastewater Reuse for Crop Production in the Water-Short Guanajuato River Basin, Mexico.", *IIMI Research Report*, vol. 41.
- Sharma, N. C., Starnes, D. L. and Sahi, S. V. (2006), "Phytoextraction of excess soil phosphorus", *Environmental Pollution*, vol. In Press, Corrected Proof.
- Sharpley, A. N., Curtin, D. and Syers, J. K. (1988), "Changes in Water-extractability of Soil Inorganic Phosphate Induced by Sodium Saturation", *Soil Science Society of America Journal*, vol. 52, no. 3, pp. 637-640.
- Shepherd, M. A. and Withers, P. J. (2001), "Phosphorus leaching from a liquid digested sewage sludge applied to sandy soils.", *J. Agric. Sci.*, vol. 136, pp. 433-441.
- Shober, A. L. and Sims, J. T. (2003), "Phosphorus Restrictions for Land Application of Biosolids: Current Status and Future Trends", *J Environ Qual*, vol. 32, no. 6, pp. 1955-1964.
- Siebe, C. and Fischer, W. (1996), "Effect of long term irrigation with untreated sewage effluents on soil properties and heavy metals absorption of leptosols and vertisols in Central Mexico.", *Pflanzenernahrsm Boden*, cited in *WHO guidelines for the safe use of wastewater, excreta and greywater (2006)*, vol. 159, pp. 357-364.
- Sims, J. T. and Pierzynski, G. M. (2005), "Chemistry of Phosphorus in Soils", in *Soil Science Society of America Book Series*, Soil Science Society of America, Madison, WI, pp. 151-192.
- Sinaj, S., Stamm, C. and Toor, G. S. (2002), "Phosphorus Exchangeability and Leaching Losses from Two Grassland Soils", *Journal of Environmental Quality [H.W.Wilson - AST]*, vol. 31, no. 1, pp. 319.
- Smith, S. R. and CAB International (1996), *Agricultural recycling of sewage sludge and the environment*, CAB International, Wallingford.
- Sparks, D. L. and Huang, P. M. (1985), "Physical chemistry of soil potassium. In R.D. Munson (ed.) Potassium in Agriculture.", *Soil Science Society of America*, , pp. 201-276.
- Stephens, W., Hess, T. and Knox, J. (2001a), "Review of the effects of energy crops on hydrology, Report to MAFF by", *Report MAFF*, vol. NF0416.
- Stephens, W., Hess, T. and Knox, J. (2001b), *Review of the effects of energy crops on hydrology*, 1, Insitute of Water and Environment, Cranfield University, Silsoe, MK454DT, UK, Insitute of Water and Environment, Cranfield University, Silsoe, MK454DT, UK.
- Tabbush, P. M., Parfitt, R. and Tubby, I. ((Revised, in press)), "Poplar and willow varieties for short rotation coppice.", *Forestry Commission Information Note 17.*, vol. 17.

- Tian, G., Granato, T. C., Pietz, R. I., Carlson, C. R. and Abedin, Z. (2006), "Effect of Long-Term Application of Biosolids for Land Reclamation on Surface Water Chemistry", *J Environ Qual*, vol. 35, no. 1, pp. 101-113.
- Timmer, V. R. and Teng, Y. (1990), "Phosphorus-induced micronutrient disorders in hybrid poplar", *Plant and Soil*, vol. Volume 126, no. 1, pp. 31-39.
- Tunesi, S., Poggi, V. and Gessa, C. (March 1999), "Phosphate adsorption and precipitation in calcareous soils: the role of calcium ions in solution and carbonate minerals", *Nutrient Cycling in Agroecosystems*, vol. 53, no. 9, pp. 219-227.
- Tuskan, G. A. and Walsh, M. (2001), "Short-rotation woody crop systems, atmospheric carbon dioxide and carbon management.", *Forestry Chronicles*, vol. 77, pp. 259-264.
- Van der Zee, S. E. A. T. M. and Gjaltema, A. (1992), "Simulation of phosphate transport in soil columns. I. model development", *Geoderma*, vol. 52, no. 1-2, pp. 87-109.
- Van der Zee, S. E. A. T. M. and van Riemsdijk, W. H. (1988), "Model for long-term phosphate reaction kinetics in soil.", *Journal of Environmental Quality*, vol. 17, no. 1, pp. 35-41.
- Watanabe, T., Kameda, S., Tadano, T. and Prasityousil, J. (1999), "Recovery of phosphorus from municipal wastewater by coagulation and the dissolution of the coagulated phosphorus by enzyme and organic acid secreted from plant roots.", *Proceedings of Environmental Engineering Research*, vol. 36, pp. 121-128.
- Westcot, D. W., Food and Agriculture Organization of the United Nations. and Ayers, R. S. (1985.), *Water quality for agriculture*, Food and Agriculture Organization of the United Nations, Rome.
- WHO (2006), "WHO guidelines for the safe use of wastewater, excreta and greywater.", *World Health Organization*, .
- WRc (2002), *Eutrophication of waters, role of phosphates, preventive measures phosphates and alternative detergent builders-*, WRC SYNTHESIS-06 2002-EC Environment Directorate, Water, Marine and Soil Unit.
- Yates, M. V. and Gerba, C. P. (1998), "Microbial considerations in wastewater reclamation and reuse", *In: T. Asano, Editors, Wastewater Reclamation and Reuse. Water Quality Management Library vol. 10*, , pp. 437-488.
- Yung, Y. L., Wang, W. C. and Lass, A. A. (1976), "Greenhouse effect due to atmospheric nitrous oxide.", *Geophys. Res. Lett.*, , pp. 619-621.
- Zdenek, F. and Demnerova, K. (2007), "Effects of wastewater irrigation on chemical, microbiological and virological status of soil.", in *Wastewater reuse - risk assessment, decision-making and environmental security*, Zaidi, M.K.; NATO ed, Springer, Dordrecht ; [London], pp. 331-336.
- Zou, X., Binkley, D. and Doxtader, K. G. (1992), "A new method for estimating gross phosphorus mineralization and immobilization rates in soils", *Plant and Soil*, vol. Volume 147, no. 2, pp. 243-250.

CHAPTER 3 : FIELD TRIAL - MATERIALS AND METHODS

1. INTRODUCTION

1.1 CRANFIELD FIELD TRIAL CONTEXT- SPECIFIC OBJECTIVE

The present chapter presents the methodology followed to set up a WaterRenew system field trial and run this field trial at Cranfield University (Bedfordshire, UK) sewage treatment works. The Cranfield field trial was one of the field trials set up across the UK as part of the EU LIFE WaterRenew project.

First, it will describe site characteristics, second justify the choice of trees' species planted, third, explain the watering system settings, and then describe the indicators of the system performances, i.e. the different parameters measured and finally; it will present the statistical analysis model utilised for data analysis.

A review of the literature (Chapter 2) to identify risks associated with irrigation of secondary treated effluent onto SRC revealed mainly the lack of quantitative knowledge on the efficiency of such systems as tertiary system or nutrient removal systems, the lack of understanding of how the system can be sustainable regarding P dynamics in soil and the lack of knowledge on the upper limits of such systems. Therefore the objectives of this field trial were:

- **Objective 1:** To quantify wastewater treatment efficiency by quantifying the main treatment processes for N and P mainly but also for K and Na and assess the relative importance of each of the compartments soil and plant.
- **Objective 2:** To identify upper limits on the operation of such systems before observing poor treatment level of effluent, or hydrological problems with permanent ponding or physiological problems with reduced tree yields or health.
- **Objective 3:** To model processes into simple equations in order to develop a design and operational tool for WaterRenew systems.

1.2 OVERVIEW

The Cranfield site was constructed in September 2005. It was constituted of 24 plots, randomly distributed, organised in 3 replicates of 4 soil covers: *willow*, *poplar*, *eucalyptus* and *unplanted* and 2 irrigation regimes: irrigated or non-irrigated.

The treatment dynamics under different covers were assessed by monitoring soil water and soil chemistry. Plots could be planted or unplanted (control to monitor tree effect). As 3 tree species were planted, species effect on treatment dynamics was also assessed. Finally, the effect of wastewater irrigation on tree growth was also studied.

The plots were 3.5 m*3.5 m size and planted with a density of 13,061 tree.ha⁻¹ (i.e. 16 trees per plot)

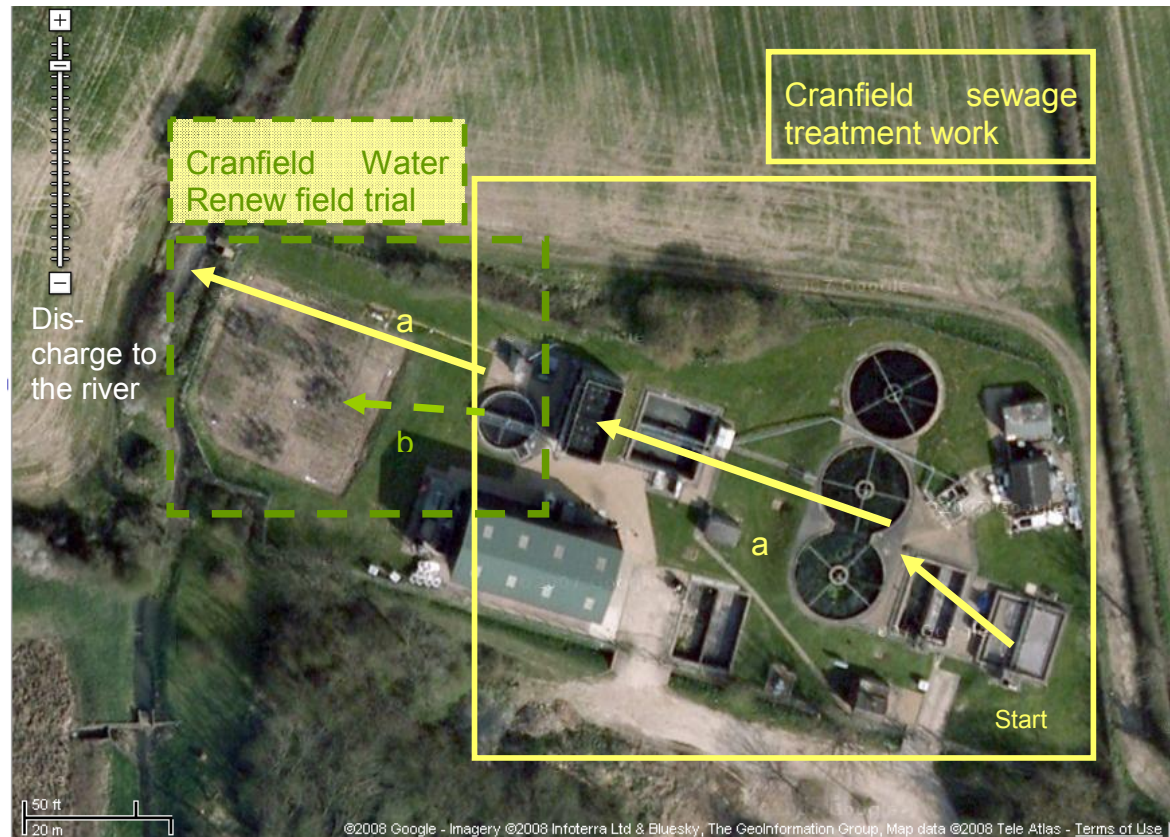
2. SITE CHARACTERISTICS

2.1 LOCATION AND SITE HISTORY

The field trial described in this project was stationed at the Cranfield University sewage treatment works. Cranfield is located at Latitude: 52.070; Longitude: -0.627, Elevation 111 m. Its national grid reference is SP9405342653.

Cranfield lies at the boundary between Bedfordshire and Buckinghamshire, in the western part of East Anglia. It was also classified Nitrate Vulnerable Zone, NVZ, (DEFRA, 2002b). Consequently, agricultural activities on the sewage treatment works were tied by The Action Programme for Nitrate Vulnerable Zones Regulations 2008 (GB, Parliament. Joint Committee on Statutory Instruments., 2008) . In particular, in a calendar year, application of livestock manure is limited to 170 kg-N.ha⁻¹ and to 250 kg-N.ha⁻¹ for spreading of organic manure. According to the regulations, for grass, N application is allowed up to a maximum of 360 kg-N.ha⁻¹ until the 01/01/2012 and then 330 kg-N.ha⁻¹ from that date onwards (DEFRA, 2002a).

The area studied was located downstream of the sewage treatment works. (cf. Picture 1)



Picture 1 Aerial picture (source Google earth) of Cranfield sewage treatment works (yellow) and field trial (green). (a) is the route of raw effluent from the entrance to the sewage treatment works to its discharge to the river (cf. 2.5). (b) is the route of secondary treated effluent from the final effluent clarifier to the water Renew field.

2.2 CRANFIELD WEATHER

Cranfield lies among the driest locations in the UK (Weatherhead and Knox, 2000). It presents a deficit of rainfall during the summer months compared to reference evapotranspiration, ET_0^1 , (Schoumans et al., 1986) (Figure 1). Therefore, there was a potential for irrigation to play a key role for yield improvement during the summer.

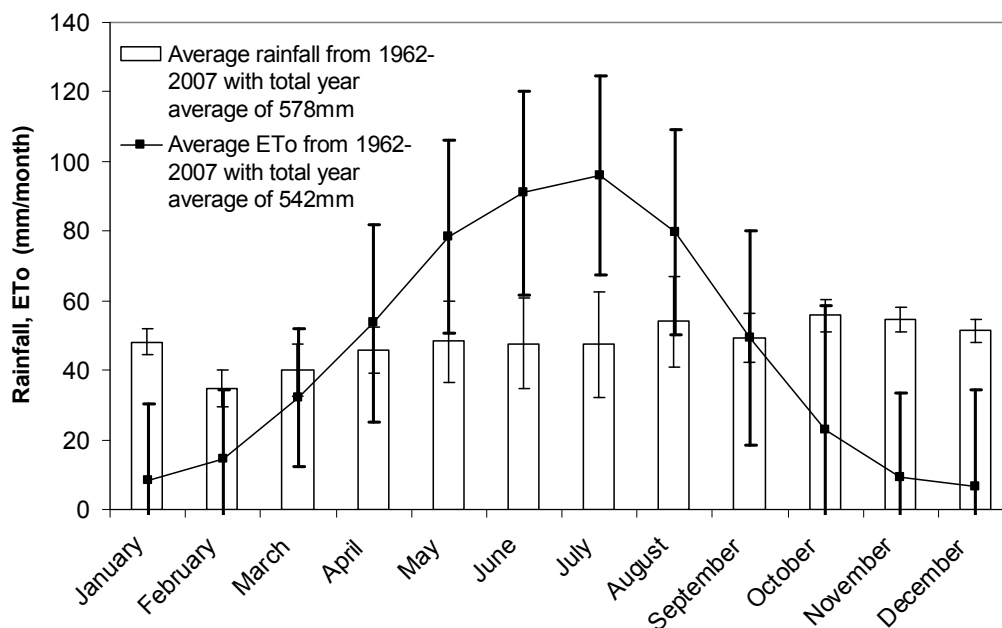


Figure 1 Monthly average rainfall (mm/month) and ET_0 (FAO Penman-Monteith reference evapotranspiration calculated with CROPWAT) at Bedford (20km from Cranfield), Bedfordshire from 1967 to 2007. Source: Silsoe automated Met Office. (Vertical bars denote standard deviation)

¹ ET_0 was the FAO Penman-Monteith evapotranspiration from "an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water." (Allen, 1998.).

The definition of this reference surface from Chapter 2 in FAO guideline 56 (Allen, 1998.) was "A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23."

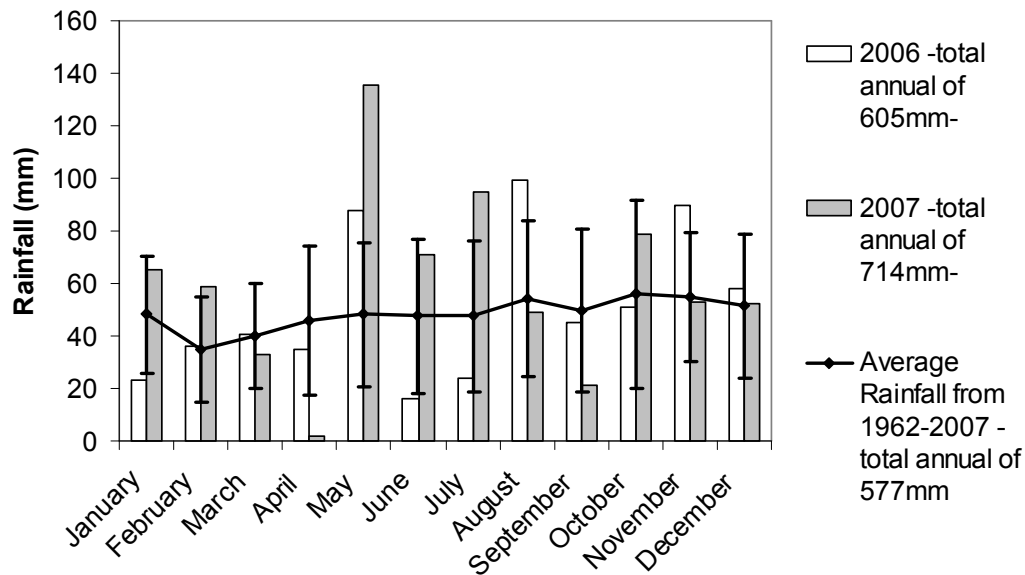


Figure 2 Monthly rainfall (mm) at Silsoe for 2006, 2007 and the monthly average for 1962-2007. Source: Silsoe met station and Met Office. (Vertical bars denote standard deviation)

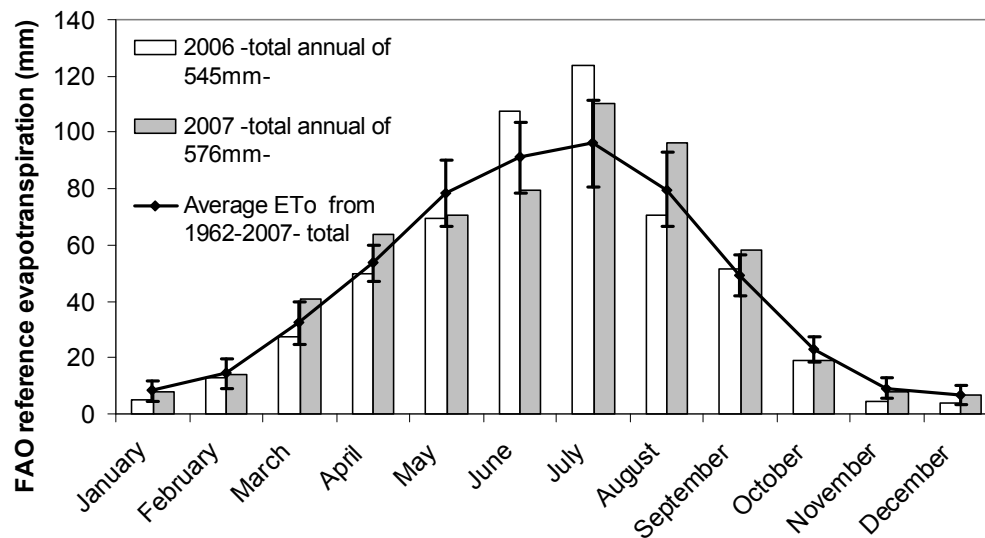


Figure 3 Monthly ET₀ (FAO Penman-Monteith reference evapotranspiration calculated with CROPWAT, mm) at Silsoe for 2006, 2007 and the monthly average for 1962-2007. Source: Silsoe met station and Met Office. (Vertical bars denote standard deviation)

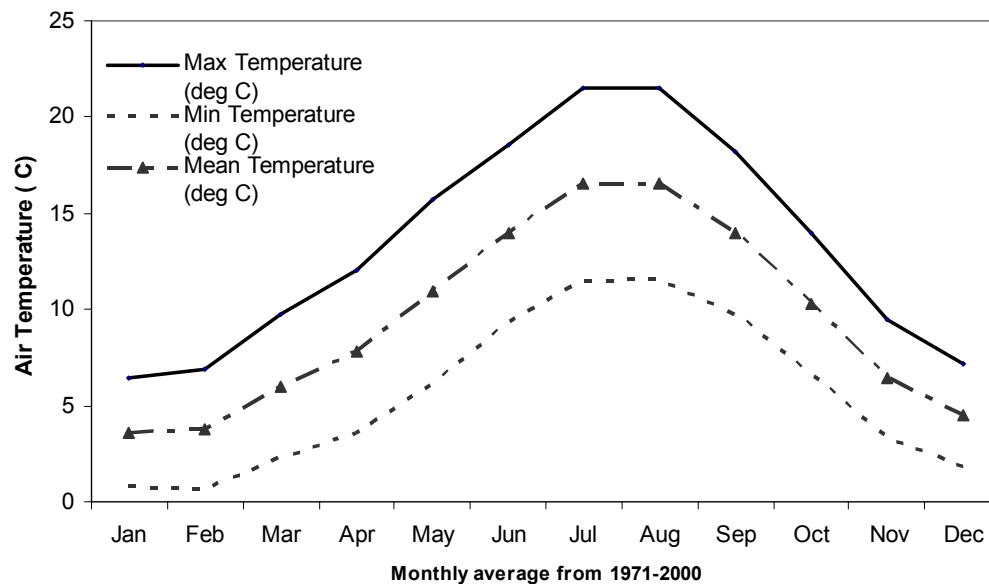


Figure 4 Mean monthly maximum, minimum and mean daily air temperature at Bedford (20km from Cranfield), Bedfordshire from 1971 to 2000. Source: Met Office.

Figure 1 to Figure 4 show respectively monthly average rainfall and ET_0 (FAO Penman-Monteith reference evapotranspiration) over 45 years from 1962-2007, monthly ET_0 (mm) for 2006, 2007 and mean ET_0 over 45 years, monthly rainfall (mm) for 2006, 2007 and mean ET_0 over 45 years recorded by an automatic weather in Silsoe at 24 km South –East from Cranfield sewage treatment works. Weather conditions at the field site during the experiment were compared to weather conditions over the last 45 years (1962-2007) to assess whether conditions during the experiment were representative of average long term conditions. ET_0 monthly data were calculated from historical average monthly data using FAO guidelines (Allen, 1998.).

From Figure 2, precipitation recorded in 2006, there was an accentuated alternation of dry months and wet months. August and November were significantly wetter than the 45 years average. The historical average monthly rainfall oscillated around 48 mm with a standard deviation of 27 mm. 2006 data oscillated around 50 mm with a standard deviation of 27 mm and 2006 was 27 mm wetter than the 45 years average.

From Figure 2, precipitation recorded in 2007, monthly precipitation oscillated even more with the highest peak at 136 mm and the lowest at 2 mm. February, May and July were significantly wetter than the 45 years average. 2007 data oscillated around

60 mm with a standard deviation of 33 mm and 2007 was 136 mm wetter than the 45 years average.

ET_0 calculated with data from 2006 were on average 5 mm lower than the 45 years average for all months except for June, July and September where 2006 data were respectively 16, 28, 2 mm higher. As a result, the annual total ET_0 was 3 mm higher as a result than the historical 45 years average.

For 2007, ET_0 was lower for January, February, March, June and July than the historical 45 years average (7, 13, 11, 40, 24 mm respectively). However, for the rest of the year, ET_0 was greater so that it resulted in an annual total ET_0 of 35 mm higher than the historical 45 years average.

For both years, there was an evaporative surplus with evapotranspiration exceeding rainfall; hence, there was more irrigation possible than could have been forecast from historical data.

According to Figure 4, on daily average, there was no major fear of negative temperatures. Again, the fact there was not much freezing temperature was a positive asset in implementing a year long irrigation system. However, as a precautionary measure and to prevent pipe and pump damage, irrigation was stopped for most of the winter 2006-2007. This could be problematic for a year long system.

2.3 SOIL CLASSIFICATION IN CRANFIELD AND EVALUATION FOR IRRIGATION

Cranfield site soil was classified as Hanslope (411d) which may be described as a slowly permeable calcareous clayey soil (Clayden and Hollis, 1984; Avery et al., 1974.; Avery, 1980; Avery, 1973).

FAO 55 guidelines (FAO, 1985) were followed to assess Cranfield soil suitability for irrigation. This evaluation will reveal if a crop response to irrigation and fertilisation is expected. Therefore, nitrogen content, available phosphorus (Olsen P, (Olsen et al., 1954.) and exchangeable potassium (MAFF, 1986.) will be measured.

Soil samples were collected before starting irrigation in February 2006 at 6 depths (10 cm, 30 cm, 50 cm, 100 cm, 150 cm, 170 cm) from each plot with an auger of 5 cm diameter. All nutrients content determinations were conducted following recommendations set out in RB 427 (MAFF, 1986.) .

2.3.1 Nitrogen content in soil

According to FAO 55 (FAO, 1985), “arable soils have a variable nitrate content ranging from less than 2 to 60 mg.L⁻¹ of nitrogen as nitrate. High levels of nitrate nitrogen may indicate that little or no nitrogen need be applied.” Cranfield soil presents nitrogen content in terms of nitrate of 29.8 mg-N.L⁻¹. It was an average value considering the range. For Total nitrogen, FAO 55 states: “Total soil nitrogen was low if it was less than 0.1 % and high if it was more than 0.3 % of the oven dry soil”. Hence, according to Figure 3, Table 1, and considering that average roots maximum density zone is not lower than 1m, total Nitrogen content was neither low nor high.

Consequently, N fertilisation can potentially enhance yield on this soil.

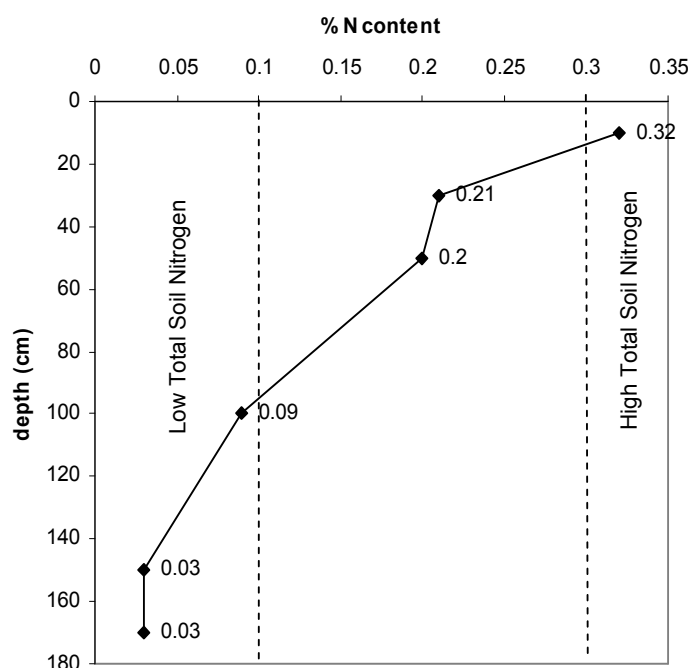


Figure 5 Mean Total Soil Nitrogen content (%) by depth in February 2006 at 6 depths from 10 cm-170 cm collected in February 2006 (n=8). According to FAO 55, if total soil N was less than (--) 0.1% , it was probable to observe a fertiliser application response, and if total soil N was greater than (--) 0.3%, it was unlikely to observe a fertiliser application response.

2.3.2 Available phosphorus in soil

According to Table 35 in FAO 55 and Figure 6, there will be not be a response to P-fertilisation because until 100 cm, extractable P content was greater than 11 mg-P.L⁻¹ of dry soil. Consequently, P fertilisation will not potentially enhance yield on this soil. Moreover, on looking at RB 209 (MAFF 2000) soil P index classification (based on the first 15 cm of soil), the average would be 23.8 mg.L⁻¹ for 0-15 cm, hence, an index P of 2. According to RB209 recommendations for fertilisation of fruit trees, vines and hops are to maintain target values of soil P index 2. Therefore, with this other assessment method, there should not be any noticeable effect of P fertilisation as Cranfield soil was at the optimum at the beginning of the experiment.

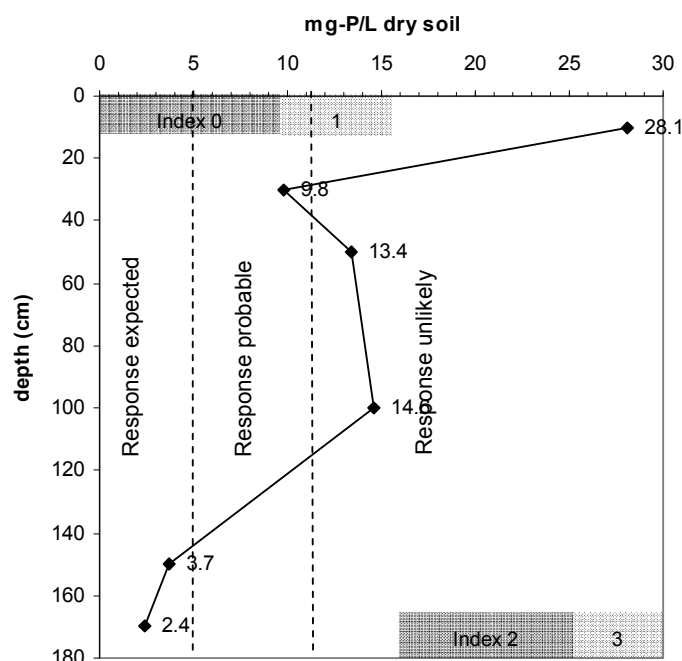


Figure 6 Average extractable P concentrations in soil (Olsen P) in mgP.L⁻¹ of Cranfield soil at 6 depths from 10 cm to 170 cm collected in February 2006 (n=8). According to FAO 55, Olsen-P less than (left --) 5mg.L⁻¹, it was probable to observe a fertiliser application response, and if Olsen-P greater than (right --) 11mg.L⁻¹, it was unlikely to observe a fertiliser application response. RB 209 indexes are also reported (MAFF 2000).

2.3.3 Exchangeable, available potassium content

According to FAO 55, “soils with less than 100 kg.ha⁻¹ of exchangeable potassium in the root zone were often responsive to potassium fertilizer”. However, if soil contains more than 300 kg.ha⁻¹ of exchangeable potassium, then, very few crops were likely to respond.

For Cranfield at 50 cm depth, available potassium was already much greater than 300 kg.ha⁻¹, measuring 1309 kg.ha⁻¹ (Figure 7). Consequently, there was no expected response to Potassium fertilisation.

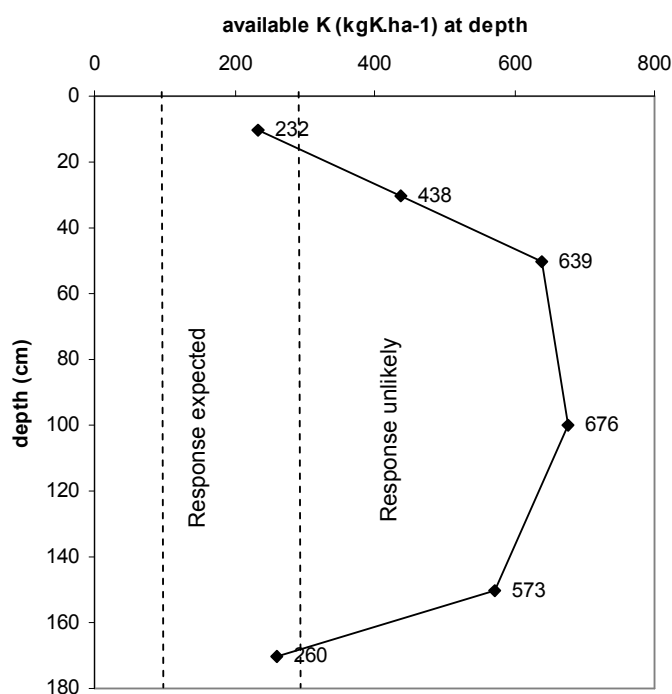


Figure 7 Average extractable K content in kgK.ha⁻¹ of Cranfield soil at 6 depths from 10 cm to 170 cm collected in February 2006 (n=8). According to FAO 55, if available K was less than (--) 100kgK.ha⁻¹, it was probable to observe a fertiliser application response, and if available K was greater than (--) 300kgK.ha⁻¹, it was unlikely to observe a fertiliser application response.

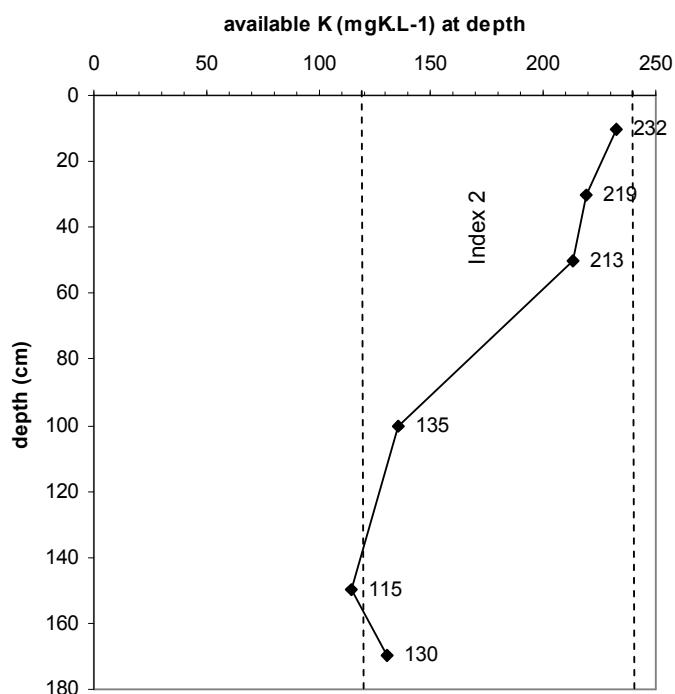


Figure 8 Average extractable K content in mg-K.L⁻¹ of Cranfield soil at 6 depths from 10 cm to 170 cm collected in February 2006 (n=8). According to RB209, index-K 2, target index, corresponds to values between 121 and 241 mg-K.L⁻¹ (--)

Moreover, on looking at RB 209 (MAFF 2000) soil K index classification (based on the first 15 cm of soil), the average available K content would be 222 mg.L⁻¹ for 0-15 cm, hence, an index K of 2+. According to RB 209 recommendations for fruits trees, vines and hops fertilisation, was to maintain target values of soil K index 2. Therefore, according to RB 209 recommendation, as soil was at index K 2, the optimum K content was reached from the start.

2.4 CHARACTERISTICS OF THE EFFLUENT IN THE TREATMENT WORK

Cranfield University sewage treatment works was designed in 1946 to treat 2000 p.e (population equivalent) effluent production. Raw effluent produced on campus was collected and directed to the sewage treatment works.

The effluent used for fertigation was a secondary treated urban wastewater.

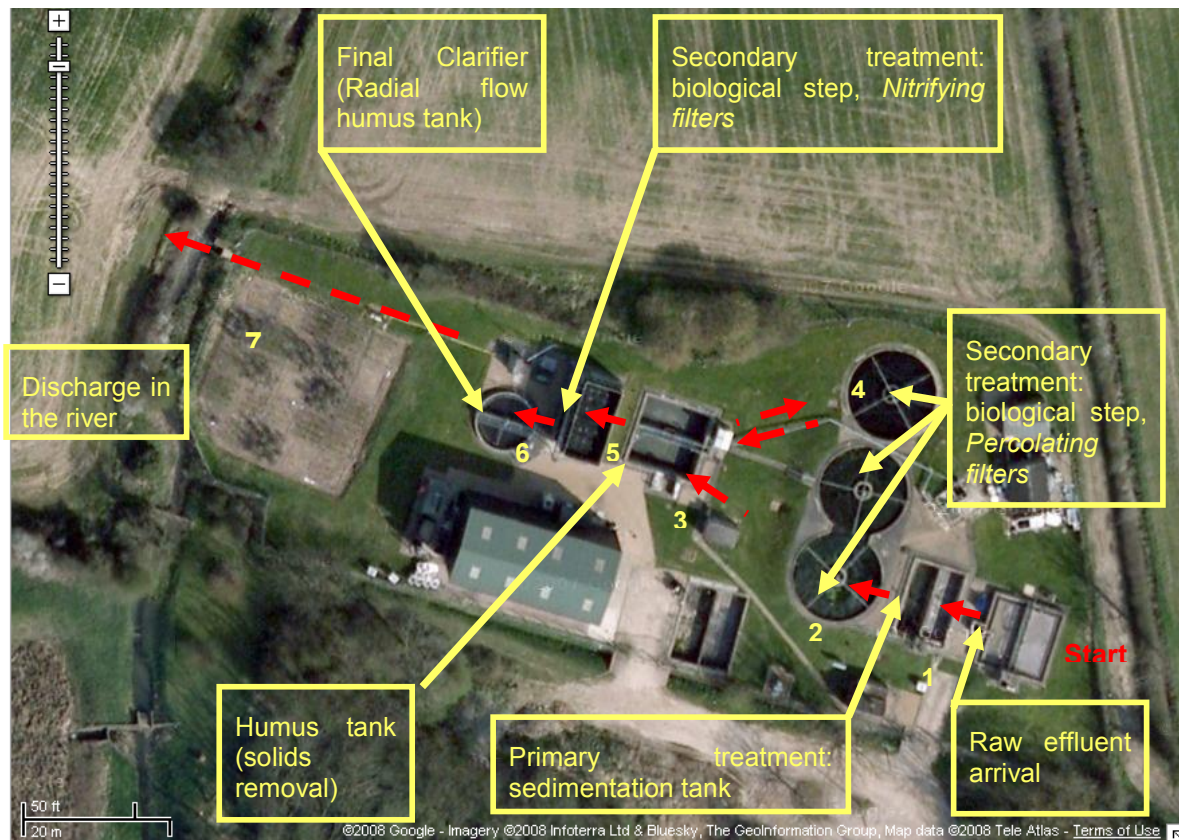


Figure 9 Sewage treatment processes on Cranfield sewage treatment works, from raw effluent arrival point, 1) the effluent goes to a sedimentation tank where primary treatment takes place with sedimentation of solids contained in the effluent. 2) The primary treated effluent is sprayed on percolating filters where the biological step takes place. 3) The secondary treated effluent is then delivered in a humus tank where solids are removed. 4) This solid removed secondary treated effluent is re-pumped into a last percolating filter tank. 5) Ammonium content of this last effluent doesn't fulfil the discharge consent limits ($>6 \text{ mg.L}^{-1}$ of NH_4), hence it was sprayed on nitrifying filters where nitrification takes place. 6) The nitrified secondary treated effluent was sent to a final clarifier, radial flow humus tank, where a final solids removal takes place. 7) this final effluent is discharged in the river Chicheley Brook.

After primary and secondary treatment, effluent was directly discharged into Chicheley Brook.

The effluent is treated to meeting the site discharge consent regulated by the Environment Agency. The discharged effluent composition is presented in Table 2. Nitrate concentrations were increased by more than 200 % from pre-treatment to discharge as a result of a nitrification phase happening at the end of the biological treatment (secondary) for the effluent to meet discharge requirements for ammonium.

Table 1 Composition of pre-treatment effluent and discharged effluent (average on 2005-2008 bi-monthly analysis, Water Science centre, Cranfield University, personal communication)

	BOD (mg.L ⁻¹)	Nitrate (mg-NO ₃ -N.L ⁻¹)	Ammonia (mg-NH ₄ -N.L ⁻¹)	Suspended Solids (mg.L ⁻¹)	pH
Pre-treatment effluent	266.5±44.5	5.6±0.68	24.9±5.44	256.3±39.3	7.7±0.2
Discharged effluent	10.2±2.4	28.5±2.2	4.3±0.6	20.9±3.8	7.0±0.2
UWWTD requirements	25 mg.L ⁻¹ and a reduction of min 70%		6 mg.L ⁻¹ and a min reduction for Total N of 70%	35 mg.L ⁻¹ and a min reduction of 70%	
<i>Reduction from pre-treatment to discharge</i>	-95%	+223%	-89%	-90%	-7%

As designed for 2000 p.e, there was no P consent, therefore, P analyses were not required (DEFRA, c2002.), however, bi-monthly phosphate concentrations were measured from July 2006 to March 2008. The average phosphate content of the discharged effluent was 4±1.6 mg-P.L⁻¹.

3. TRIAL DESCRIPTION

3.1 EXPERIMENTAL DESIGN

The Cranfield site was constructed in September 2005 (22 m by 22 m). It was constituted of 24 plots, randomly distributed, organized in 3 replicates of 4 soil covers: *willow*, *poplar*, *eucalyptus* and *unplanted* and 2 irrigation regimes: irrigated or non-irrigated.

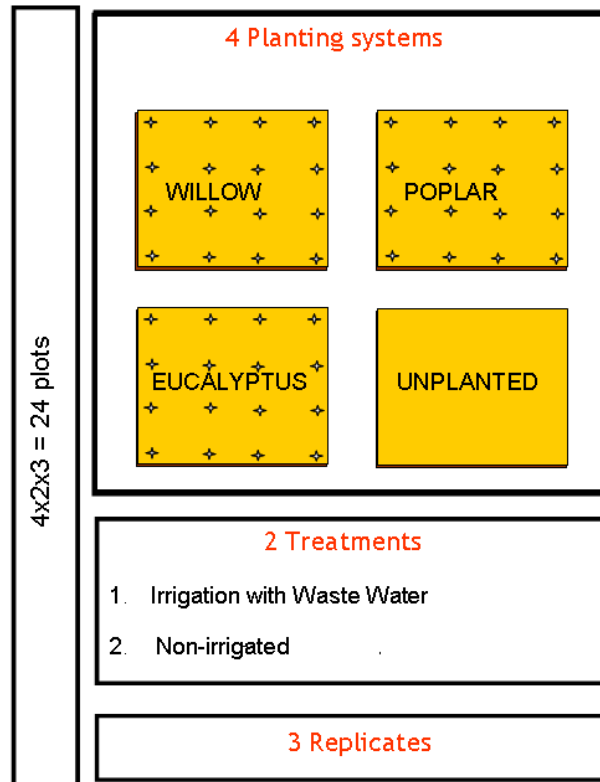


Figure 10 Experimental design

3.2 PLOT LAYOUT

With the experimental design explained, the plots were laid out on a total field trial area of 22 m by 22 m. 4 dip wells were installed at the 4 corners of the field to permit groundwater sampling. As the river was parallel to the field, the 2 dip wells further to the river were considered as the upstream dip wells, as upstream to the field trial, and the 2 closer to the river as the downstream dip wells (as downstream to the field trial, Figure 10).

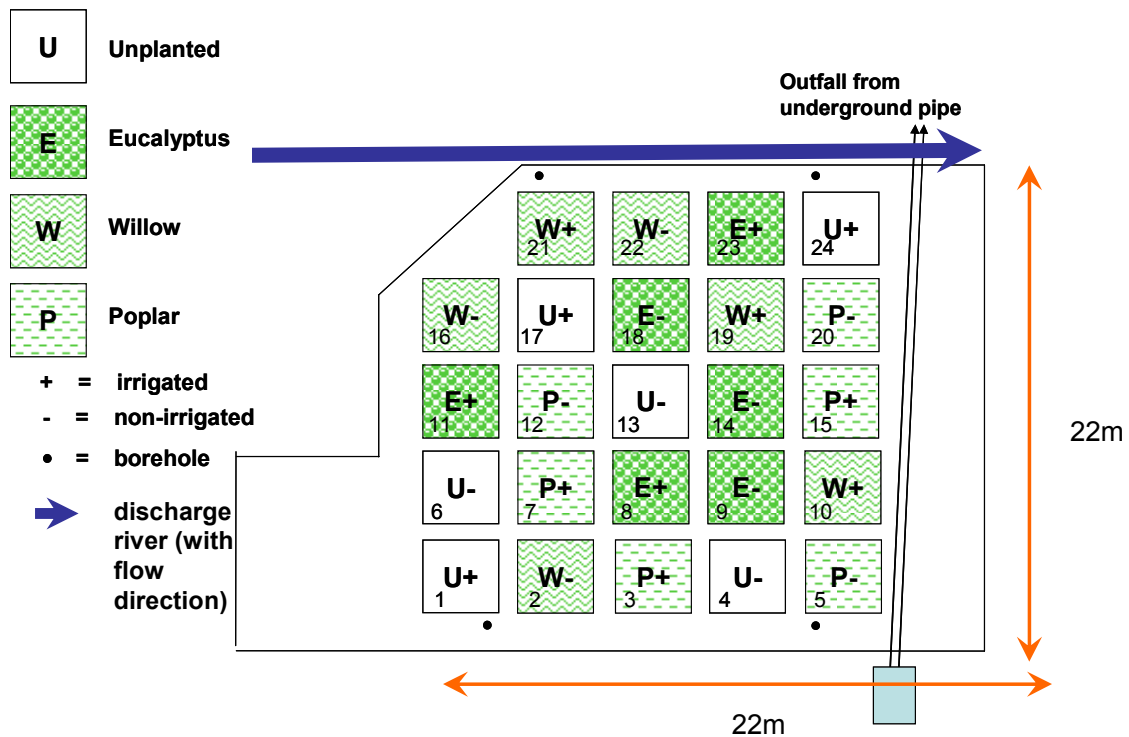


Figure 11 Cranfield site field trial map, localisation of 24 randomly distributed plots, 3 replicates of 4 covers, unplanted, eucalyptus, willow and poplar, irrigated or not.

3.3 PLOT CONSTRUCTION

The field was prepared in September 2005. Prior to the experiment, this part of the sewage treatment works was uncultivated grassland. The trial dimensions were: 22 m by 22 m (cf. Picture 2).

Prior to planting, the field was weeded and ploughed. Then, it was levelled with soil collected from the surroundings of the sewage treatment works.

Polythene sheets of 60 cm width were installed as on Picture 2 to individualise the different plots on separating them up to 50 cm depth with the polythene sheet.



Picture 2 Field trial preparation.

The pipe connecting the final clarifier tank and the discharge point was passing on the side of the field. However, there was a historical pipe, now filled, passing under the field area forming a triangle with the actual pipe.

4. TREE SPECIES CHOICE

4.1 TREE SELECTION

Trees in a WR system were to be grown in short rotation coppice (SRC). SRC is a cultivation method for fast growing trees planted densely and harvested on short cycles of 2 to 5 years (DEFRA, 2002.).

In the UK, willow and poplar trees are species of choice for SRC. As one of the objectives of a WR system was to apply a maximum portion of treated wastewater produced at the sewage treatment works, the following requirements were taken into account when woody crops were selected:

- Coppicable meaning the stems can be cut down. New stems can regenerate for between 2 to 5 years before being harvested again (DEFRA, 2002.).
- Fast growing which implies a great water and nutrients' use capacity
- Not sensitive to very wet conditions and preferably tolerant to very tolerant

- Well adapted to Cranfield, Bedfordshire conditions in terms of pests (rust, (Tabbush et al., (Revised, in press)) and temperature (cf. hardiness)
- Very tolerant to the average components of sewage (cf., Na and B as boron in particular)

For the Cranfield trial, the following cultivars were selected in accordance with the previous criteria:

- For poplar, *Populus*, the cultivar *Trichobel*¹ = *P.trichocarpa* x *P.trichocarpa*, *Trichobel* variety was used for its resistance to rust and because it keeps its leaves longer than other varieties. They were harvested from a poplar plantation on the Silsoe Campus farm, Bedfordshire. (pers comm.)
- For willow, *Salix viminalis*¹, the cultivar Resolution, variety code LA980414. The *Resolution* variety was selected for its resistance to rust and for its fast growing property. They were harvested in the Rochester national Willow Farm.

In contrast to these species, Eucalyptus trees were also chosen. They can provide a comparison with conventional UK SRC because they are evergreen trees and non-indigenous specie and planted as single stem. Thus, for Eucalypts, the following species were selected:

- *Eucalyptus gunnii* , as a subalpine was able to cope with temperature as low as -14°C (Scarascia-Mugnozza et al., 1989)
- *Eucalyptus nitens* , as one of the major hardwood species cultivated for its high tolerance to frost (Nielsen, 1990)

4.2 PLANTING

Poplars and willows were planted as cuttings of 20 cm length for the first time in October 2005 according to SRC guide (DEFRA, 2002.). They were planted at a density of 13,060 trees.ha⁻¹. This density was also in accordance with recent recommendation (Tabbush et al., (Revised, in press)). Eucalypts were also planted with the same density.

But the wet and cold conditions were too long to permit establishment of the trees. The willows became infected by rust, the poplars rotted and the *E.nitens* trees did not

¹ These cultivars are the one used when the field was replanted in spring 2006. The initial cultivars used in October 2005 were different for willow. It was an older variety of *S.viminalis*, and it got infected by rust during winter 20005-2006. However, *Trichobel* was initially planted as well and replanted in spring 2006.

survive the wet and cold conditions of the winter 2005-2006.

For this reason, willows were replanted on the 17th of March. It was more difficult to assess the health of poplars cuttings therefore, it was decided to monitor them for longer. However, it became clear that the cuttings were infected by rust and the decision to replant poplars was taken. And they were replanted on the 21st of April 2006.

Eucalyptuses were not replanted at this stage but 52% of the *Nitens* were dead (28/05/2006) and they were replaced by *Gunnii*. 15% of the *Gunnii* were dead on the 28 May 2006. Accordingly, on the 13th of June 2006, only *E. gunnii* was considered for Cranfield field trial and all dead trees were replaced by new one season young trees grown in pots in June 2006.

On each of the planted plots there were 16 trees. The 4 inner trees were measured and the area delimited was used for measurements. The remaining 12 trees were “buffer” trees so that edge effect and neighbourhood effect would be levelled.

5. IRRIGATION SYSTEM DESIGN AND SETTINGS

5.1 WATERING PHILOSOPHY

One of the objectives of this field trial was to study how much effluent can be delivered on tree's planted plots managed as SRC.

However, conventional SRC practices can include fertilisation but do not include irrigation (DEFRA, 2002) and for this reason, the control irrigation regime chosen was no irrigation.

A WR system pursues a double objective: high yield production and on the wastewater treatment side, maximisation of the amount of wastewater daily applied. But this double objective has to be reached whilst minimising potential risks of groundwater or soil contamination with nutrients or pathogens (Scott et al., 2000).

Consequently, the risk associated in a WR system will be over-irrigation, but how could “over-irrigation” be defined? The upper boundary of the WR system is limited by the trees and the lower limit by soil at 60 cm depth.

Over-irrigation could happen at three levels:

- Chemically: the quality of the effluent entering the system is not improved on leaving the system

- Physiologically: the amount of effluent added to the system is causing water stress to plants and instead of enhancing growth, will slow growth or even kill them.
- Hydrologically: the amount of effluent added is not entering the system in the case of loss by runoff, or not staying in the system, in the case of bypass flow with subsequent significant amount of drainage.

Controlling the irrigated volumes will limit risks associated with hydrological concerns. In effect, the system was designed to deliver effluent onto the field whenever soil moisture content measured at 10 cm depth fell under field capacity ("the presumed water content at which internal drainage flow ceases" (Hillel, 1980). Thus, the aim was to prevent surface runoff and significant drainage. This would also minimise chemical risks. This was because if field capacity was maintained, it would prevent drainage, therefore, it would maximise the residence time of the applied effluent. Consequently, it would maximise the time chemical reactions of wastewater polishing to happen on maximising contact time of effluent nutrients and soil matrix.

Thus, an automated soil moisture content dependent dripped irrigation system was designed and implemented. Therefore, the choice was made to keep the soil moisture equal for all plots and not the amount of nutrients applied. Indeed, because the volume of effluent irrigated could vary with each of the four cover, the amount of nutrients will as well.

Field capacity also provided a beneficial water content for roots' development. Thus, maintaining field capacity will maintain soil water content to an optimum for plant growth.

5.2 HOW TO DETERMINE FIELD CAPACITY

Field capacity is often taken to be the water content of a bare soil, that had been at saturation, following 48 hours of drainage whilst ensuring the prevention of soil evaporation (by use of a plastic cover). In this state the larger soil pores are unsaturated and permit aeration. A moisture content (% by volume) which was considered to represent field capacity for the soil at the Cranfield sewage works site was determined by field measurement and related to the laboratory-determined water release curve. There are a range of soil water potentials which are assumed to be related to field capacity, ranging from -60 to -300 cm (Ehlers and Goss, 2003), i.e. -6 to -30 kPa and pFs of 1.8-2.5. In the UK, "retained water capacity" is often determined at

-50 cm, or -5 kPa (Hall et al., 1977). This is a pF value of 1.70. In continental Europe, a pF value of 2.5 or -200 cm was typically used. Because of this variation, field capacity value was refined with field adjustment at the beginning of the experiment.

The water release curve was determined by sand table measurements and pressure membrane measurements on 7 undisturbed samples (cores of 2 cm height and 5.4 cm diameter) collected at 10 cm depth from 7 plots picked randomly (Figure 12)

These data corresponded to the depth where the Theta-probes were placed to measure water content.

The volumetric water content related to the range of definition for field capacity (60 cm to 300 cm head) water tensions ranged from 68 % to 58 %.

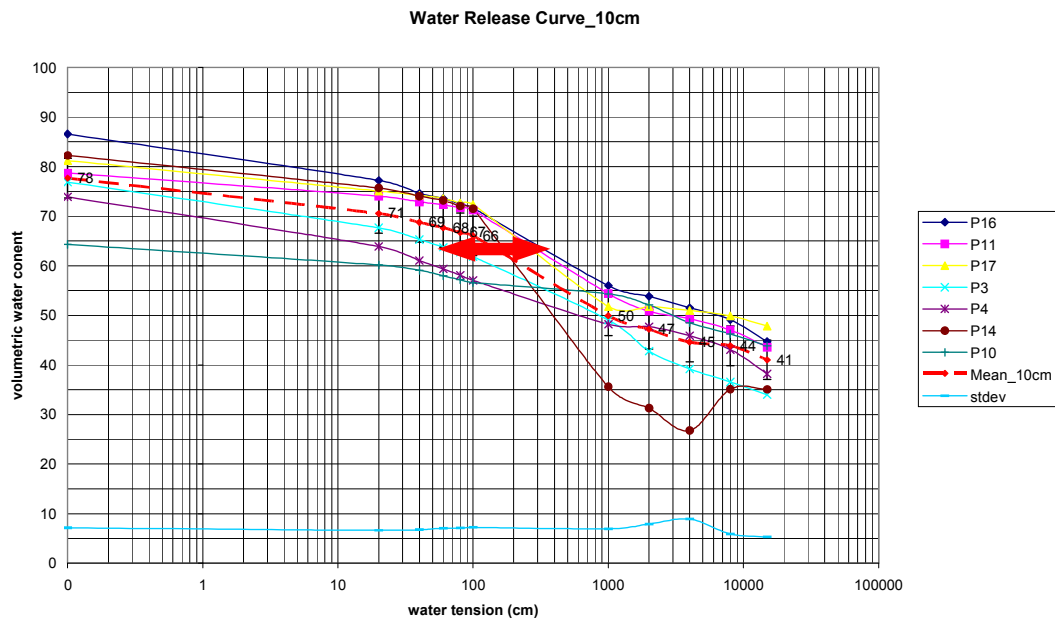


Figure 12 Water release curve for the first 10 cm of soil on 8 plots. (→) Field capacity range.

5.3 IRRIGATION SYSTEM SETTINGS (MATERIAL)

All the piping of the irrigation system was installed on the 3rd and 4th of May 2006. A pump connected the main pipe (1" diameter) to lateral pipes (2 pipes of 16 mm diameter per plot). The drippers were connected to the lateral pipes (Figure 13). As effluent contained suspended solids, taps were added at the end of each lateral pipe allowing them to be flushed regularly. The drippers were installed first at a distance of 10 cm from the trees and second in order to be the furthest from one another and to try to have the most homogeneous drippers' distribution on the plot (Figure 13).

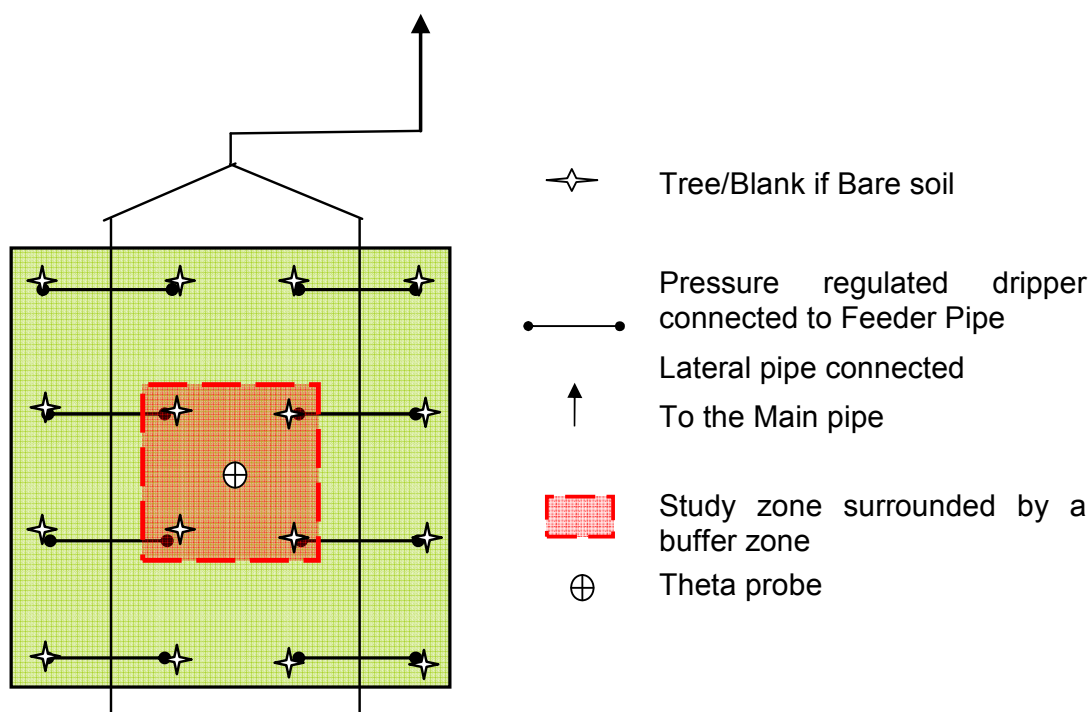


Figure 13 Irrigation system layout.

The Theta-Probe (Soil moisture sensor SM200, Delta-T), measuring moisture content to assess if the pump should be turned on or not was placed in the middle of the plot at 61 cm from the four inner drippers. As irrigation settings should avoid runoff, SM200 probes were placed close enough to the soil surface and as their measuring parts were 7 cm long, they were placed at 10 cm depth. The irrigation system was controlled by a Campbell data logger. The logger was programmed to run every minute from 6.00 am to 6.00 pm. For one hour in every four hours, it calculated mean volumetric water content for each block of plots with the same trees and compared it to a threshold water content, laboratory determined field capacity. If this calculated value was less

than the threshold, then the pump was tuned on.

6. DATA COLLECTION-MONITORING SYSTEM

To assess the impact or effect of irrigating a SRC with wastewater, each of the soil, water and plant compartments were monitored from February 2006 until February 2008. In the following section, the sampling methods, analyses performed and the standard methods used for each compartment are presented.

6.1 SOIL MONITORING, SAMPLING AND ANALYSES

Soil samples were collected with a 5 cm diameter auger from each plot during the 3 years in February at 3 depths (0-10 cm, 20-30 cm and 40-50 cm). Maximum density of roots for willow, poplar and eucalyptus was around 30 cm and with the 3 depths screened, effect of roots uptake should be identifiable. As the field experiment was replicated, only one sample was collected at each depth from each plot.

All the analyses were conducted according to the Reference Book 427 (MAFF, 1986.).

Accordingly, apart from mineral N determination in soil when no preparation was needed (sample type I, Table 2), soil samples were air-dried and sieved to pass 2 mm before any analyses were performed (sample type II). For Total C and N, samples of type II were oven dried (105 °C for 2 hours) and ground through a 0.5 mm sieve and referred to as sample type III. To determine SAR (sodium adsorption ratio), Na and Ca+Mg concentrations were determined on saturated paste extract; sample type IV.

However, for bulk density and water release curve, undisturbed soil core samples were collected from the surface of each plot (0-3 cm) using density rings (5 cm diameter and 1.2 cm length), sample type V. And for infiltration rate determination, undisturbed soil core samples were collected with big density rings (10 cm diameter and 12.5 cm length), sample type VI.

The analyses performed on these different samples are summarised in Table 2 with the corresponding methods and standard operating procedure (SOP). As standard methods were followed, they were not described in detail.

Remark:

For mineral N, i.e. TON and Ammonia, measurement has to be conducted on moist fresh samples (MAFF, 1986.). However, these analyses were conducted on samples kept in hermetically sealed bags, in the dark, at 4°C for 6 weeks for 2006. But, the

analyses were conducted on samples kept less than a week in the dark at 4°C, i.e. fresh samples for February 2007 and February 2008. There could have been a comparability problem because of this difference at the beginning of sample handling. But on opening the 2006 February samples' bags, there was no smell of gas such as ammonia that could have been produced from nitrogen gasification. And therefore, it was reasonable to consider 2006 samples measurements realistic.

Moreover, in February 2006, as only eucalyptus young trees were planted and alive but dormant, and no irrigation applied yet, for this reason, only 8 plots were sampled. And in February 2007, the same plots were sampled and replication of the extractions of TON and Ammonia was performed. Finally, in February 2008, the 24 plots were sampled and no replication on the measurements was performed as the 24 plots represented 3 replicates of 8 different plots. However, even for February 2008, only the 8 plots sampled in 2006 and 2007 were considered.

Table 2 Analyses on soil samples and methodology

Soil Physical characteristics		
Soil analysis and unit	Method/ Equipment	Standard Operating Procedure
Soil texture (particle size analysis) (sample type II)	Pipette method	NR-SAS/SOP 5 BS 1377:Part 2:1990
Moisture content (sample type I)	Oven drying method	NR-SAS/SOP 3 BS 1377:Part 2:1990
Infiltration rate (mm.h ⁻¹) (sample type VI)	Falling head method based on Darcy law	(Reeve et al., 1957)
Bulk density (g.cm ⁻³) (sample type V)	Oven drying method	NR-SAS/SOP 25 BS 1377:Part 2:1990
Water release curve (sample type V)	- Sand table - Pressure membrane methods	(Avery and Bascomb, 1982) Hall et al., 1977
Soil chemical characteristics		

Soil analysis and unit	Method	Standard Operating Procedure
Total C (mg/kg soil) (sample type III)	Catalytic tube combustion/ Elemental Analyzer	NR-SAS/SOP 11
Total N (mg/kg soil) (sample type III)	Catalytic tube combustion/ Elemental Analyzer	NR-SAS/SOP 11
Total P (mg/kg soil) (sample type III)	- Aqua Regia digestion -spectrophotometer	NR-SAS/SOP 17
Total K (mg/kg of soil) (sample type III)	- Aqua Regia digestion - AAS ²	NSRI/AL/SOP 17
NH ₄ -N (mg-N.L ⁻¹) (sample type I)	-KCl extraction - SFA ³	NSRI/AL/SOP 13
TON-N (mg-N.L ⁻¹) (sample type I)	-KCl extraction - SFA	NSRI/AL/SOP 13
Available P (mg/kg of soil) (sample type II)	- Olsen P, NaHCO ₃ extraction - spectrophotometer	NR-SAS/SOP 15 Olsen et al., 1954
Degree of Saturation in Phosphorus (DSP) (sample type II)	-Oxalate ammonium NH ₄ OCOCOONH ₄ . H ₂ O extraction - spectrophotometer	Schoumans et al., 1986
Phosphorus saturation index (PSI) (sample type II)	Isotherm method	Nair et al., 1984

² AAS: Atomic Absorption Spectrophotometer

³ SFA: Segmented Flow Analysis

Extractable Na (sample type II)	-Ammonium nitrate extraction -AAS	NSRI/AL/SOP 14
Available K (mg/kg of soil) (sample type II)	Reference Book 427 (MAFF, 1986.; MAFF, 1986.).	NSRI/AL/SOP 14
Soil electrical conductivity EC _e (sample type IV)	EC _e -meter	NR-SAS/SOP 14
Soil pH (1:2.5 w/w soil, water ratio) (sample type II)	pH-meter	NR-SAS/SOP 6 Reference Book 427 (MAFF, 1986.; MAFF, 1986.) BS 1377:Part 3:1990
Organic Matter (%) (sample type II)	Loss on ignition (furnace at 450 °C)	NR-SAS/SOP 23 BS 1377:Part 3:1990
Ca+Mg concentration (meq.L ⁻¹) (sample type IV)	Titration with EDTA	(Richards and Allison, 1954.)
Na concentration (meq.L ⁻¹) (sample type IV)	AAS	(Richards and Allison, 1954.)

6.2 SOIL WATER MONITORING, SAMPLING AND ANALYSES

6.2.1 Soil water sampling settings

6.2.1.1 Depths of sampling of soil water

To define depths for sampling, we have to consider the root average depth.

On the plot, three energy crop species were planted; Willow (Resolution), Poplar (Trichobel) and Eucalyptus (*E.gunnii*). These trees were known for their superficial root systems.

Studies confirmed that the majority of willow roots were located in the top 10-20 cm of the soil (Volk et al., 2001), (Rytter and Hansson, 1996), (Crow and Houston, 2004). Poplars have roots a little deeper but remain superficial with more than 50% of fine root biomass of hybrid poplar in the soil to depth of 3.1m was found in the first 36cm of soil (Heilman et al., 1994),(Crow and Houston, 2004). For eucalyptus (*E.nitens*), Moroni et al 2002, found that more than 50% of the root mass densities were located between 10 and 20 cm depth, both in irrigated or drought stressed conditions. Considering the literature review, only one (Trindade et al., 1997), (Spangenberg and Kolling, 2004-02-01), (Vos and van der Putten, P.E.L., September 2004) or two (Liedgens et al., 2004) to a maximum of three (Vos and van der Putten, P.E.L., September 2004) depths were considered for soil water sampling in studies of nutrient leaching. As the water table was expected to be around 1 m depth with a shallowest level close to 80 cm, the two depths 30 cm and 60 cm were considered for soil water sampling, and with probes installed with a slight angle (45°) in order to sample under the same vertical point.

The analysis of the 0.30 m depth soil water should provide information about the “plant effect” on water treatment and the 0.60 m will provide two kinds of information, i) a possible “soil effect” on water treatment and ii) the composition and quality of the water going to recharge the aquifer (cf. Figure 14).

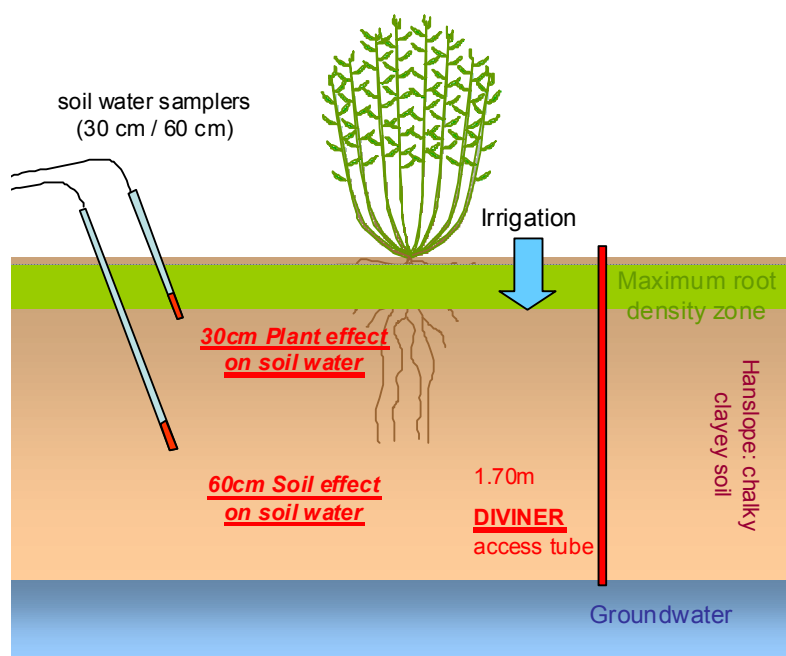


Figure 14 Model of the sub-soil organization once the crop will be established (Oz dimension)

6.2.1.2 Suction cup sampling area

The radius of the recharge area for a suction cup sampler lies between 0.1 m to 0.5 m (Grossmann et al, 1991) and considering the average infiltration rate on the set of plots (results from falling head permeameter measurements 5 cm/h \pm 10 cm/h then 100 times greater than the infiltration rate considered), the diameter of the suction cup sampling area shouldn't be greater than 50 cm (Weihermuller et al., 2005).

Then, if the suction cup samplers were at a distance of 50 cm in the three dimensions of space, it should be safe. So the question was where to install the suction cup samplers around these 4 inner trees.

It was more relevant to choose one dripper and try to collect the water it has delivered in the soil profile. Then it means that the two samplers should be installed in a way they can "see" the same water, more or less treated, at their depth.

One assumption was that after a certain time, the root system will form a continuous "mattress" at an average depth of 20 cm; roots of adjacent trees will join. A preferential development should occur in the direction of each dripper. Then, in theory, once this mattress is established, the location in the xOy dimension of the 30 cm depth suction cup samplers will not matter. But this continuous mattress might take a year to really establish.

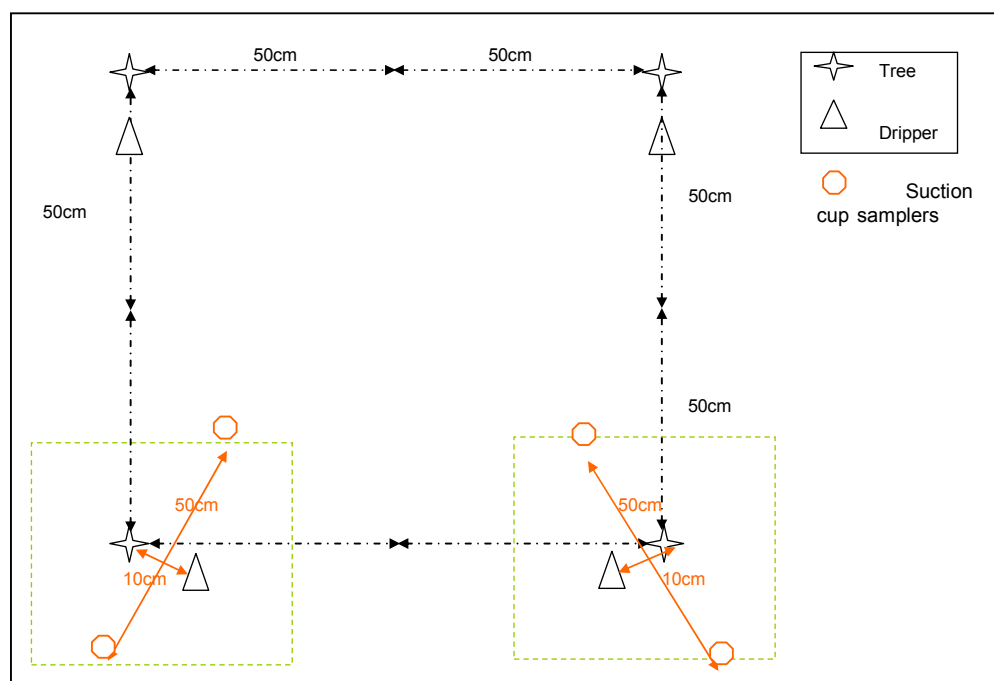


Figure 15 Air view of the middle of the plot (4 inner trees) and localization of the suction cup samplers.

Then, a compromise would be to choose one inner tree among the two that are furthest from the DIVINER access tube that could be a preferential water path. Then install the two suction cup samplers at equidistance of the tree and dripper (25.5 cm as the hypotenuse of a rectangular triangle of 25 cm and 5 cm edges) and at 50 cm from one another as showed Figure 15.

6.2.2 Sampling frequency in space and in time

As we have three replications of each condition, irrigation regime, (i) with waste water irrigation and (ii) without waste water irrigation, and crops (a) willow, (b) poplar, (c) eucalyptus, (d) without crops, we consider not needing replication for one depth. The plot replication will be the depth replication.

As the experiment ran for two years, and considering sampling frequency in the literature on such experimental duration (Trindade et al., 1997; Spangenberg and Kolling, 2004 ; Dieffenbach et al., 1997), we sampled soil water on a basis of every two weeks, and it could have been reduce to every week during autumn when rains added more water.

6.2.3 Material and methods for soil water and groundwater sampling

6.2.3.1 *Material: suction cup samplers for soil water*

Two types of cup samplers were available on the market, the ceramic suction cup samplers and Teflon suction cup samplers.

Ceramic suction cup samplers were cheaper (Liedgens et al., 2004) than the Teflon suction cup samplers (PRENART Super Quartz, Prenart Equipement ApS).

On the practical point of view, there was no report in the literature that recommended one or the other cup samplers.

But, several studies were conducted to characterize the phosphorus sorption properties of ceramic cups (Tischner et al., 1998-09-20). Zimmermann et al. (Zimmerman et al., 1978) found that only 43% of phosphates were recovered after being passed through a ceramic cup. Therefore, DVWK (1990) recommends not using ceramic water samplers for determining soil solution phosphorus.

However, other studies, e.g. Jones et al. (1995), concluded that when comparing the soil solution samples extracted with polysulfone fibres with those extracted by ceramic suction samplers, no significant differences in solute concentrations were observed and phosphate was one of these.

Prenart Teflon cups will be used; 24 of the PRENART MOVABLE SUPER QUARTZ with 55 cm PVC tube of 2.1 cm diameter and handle and 24 of the PRENART MOVABLE SUPER QUARTZ with 110 cm PVC tube 2.1 cm diameter and handle.

6.2.3.2 Methods for soil water sampling

Vacuum ranging from -50 kPa to -80 kPa was applied for 24 hours, as reported in literature (Trindade et al., 1997; Spangenberg and Kolling, 2004), on each of the suction cup samplers fortnightly. Then, soil water collected in soil water suction cup samplers was stored in plastic bottles of 60 mL at 4°C and analysed within a week.

6.2.4 Methods for groundwater sampling

For groundwater, enough samples (>10 mL) were collected by suction with a 1 cm diameter polythene tube of 1.50 m and filtered within 3 days through Whatman n°2 filter paper to retain debris for machinery concerns.

6.2.5 Chemical analyses on soil water and groundwater

As the objective was to assess energy crops ability to polish waste water as a tertiary treatment, nutrients' concentrations in soil water were monitored, in particular N and P components.

Samples did not need to be filtered as PRENART Super Quartz, Prenart Equipement ApS pore size was of 2 µm. When sampled volumes were under 0.1 mL (or a drop), the samples was discarded. A minimum of 10 mL was necessary to conduct all the analysis, therefore, when less than 10 mL was sampled, samples were diluted with distilled water to make up the necessary volumes.

The analyses performed on soil water samples were summarised in Table 3 with the corresponding methods and standard operating procedure (SOP). As standard methods were followed, they were not described in details.

Table 3 Analyses on soil water samples and methodology

<i>Soil analysis and unit</i>	<i>Method/ Equipment</i>	<i>Standard Operating Procedure</i>
Total N (mg-N.L ⁻¹)	SFA ⁴	NR-SAS/SOP 28
Total P (mg-P.L ⁻¹)	SFA	NR-SAS/SOP 28
NH ₄ -N (mg-N.L ⁻¹)	SFA	NR-SAS/SOP 31
TON-N (mg-N.L ⁻¹)	SFA	NR-SAS/SOP 32
PO ₄ (mg-P.L ⁻¹)	SFA	NR-SAS/SOP 33
K (mg-K.L ⁻¹)	AAS ⁵ Or flame photometer	NR-SAS/SOP 17
Na (mg-Na.L ⁻¹)	AAS Or flame photometer	NR-SAS/SOP 17
Soil water electrical conductivity EC _e conducted within 24 hours after collection	EC _e -meter	NR-SAS/SOP 14
Soil water pH conducted within 24 hours after collection	pH-meter	NR-SAS/SOP 6
Ca+Mg concentration (meq.L ⁻¹)	Titration with EDTA	(Richards and Allison, 1954.)
Na concentration (meq.L ⁻¹)	AAS	(Richards and Allison, 1954.)

⁴ SFA: Segmented Flow Analysis with Burkard Automatic Ion Analysers

⁵ AAS: Atomic Absorption Spectrophotometer

6.3 PLANT MONITORING, SAMPLING AND ANALYSES

6.3.1 Plant growth monitoring

Plant measurements were recorded for two purposes:

- To record growth and growth trend
- To generate allometric relationships between different measurements in order to assess total biomass evolution and final yields.

Therefore, non-destructive measurements took place monthly during the growing season (March-October 2006, 2007). Intensive measurements were conducted during summer 2006 with fortnightly measurements. On each plot, the 4 inner trees were measured for: stem diameter at 8 cm from ground, stem length and Leaf Area Index (LAI⁶, with SunScan Delta-T)

The choice of the parameters measured was justified by Breuer et al. (2003). Breuer identified the following parameters as most common, necessary and sufficient to model trees growth:

- interception capacity, maximum leaf area index, rooting depth, plant height, stomatal conductance, stand age, basal area and stock density.

6.3.2 Wood and leaf sampling methods

To monitor eventual leaf nutrient content evolution with tree development stage, leaves from a stem for poplar and willow or a branch for eucalyptus were collected in October 2006 and then July, August, September, October 2007 and for eucalyptus, in February 2008 during the first harvest.

For wood, only one sample was collected for nutrient analysis in February 2008.

6.3.3 Wood and leaf material nutrient analysis

Leaf and wood materials were prepared according to RB 427 (MAFF, 1986.). Leaves were dried for 18 hours at 105 °C and wood was dried until it reached constant weight, which resulted in 48 hours at 100 °C.

The dried materials were shredded and ground to pass through 1 mm sieve prior to chemical analyses.

⁶ LAI: "area of leaves per area of underlying ground surface averaged over a large area. Only one side of leaves is counted (m².m⁻²)" (Allen, 1998.)

The analyses performed on plant material samples were summarised in Table 4 with the corresponding methods and standard operating procedure (SOP). As standard methods were followed, they were not described in detail.

Table 4 Analyses on soil water samples and methodology

<i>Soil analysis and unit</i>	<i>Method/ Equipment</i>	<i>Standard Operating Procedure</i>
Total C (% of total mass)	Catalytic tube combustion/ Elemental Analyzer	NR-SAS/SOP 11
Total N (% of total mass)	Catalytic tube combustion/ Elemental Analyzer	NR-SAS/SOP 11
Total P (mg/kg biomass)	- Aqua Regia digestion -spectrophotometer	NR-SAS/SOP 12
Total K (mg/kg biomass)	- Aqua Regia digestion - AAS ⁷	NR-SAS/SOP 12

6.4 HYDROLOGICAL MEASUREMENTS

6.4.1 THETA PROBE on each plot

One Theta probe (Delta-T) was installed on each plot.

The Theta probe reading provided the reading of volumetric moisture content responsible to turn on or not the pump in the irrigation system. In fact the average of the readings of the 3 replicates of the same type of tree growing and irrigation settings, was calculated every minutes and compared to threshold moisture content; field capacity. Then, if the aim was to discharge as much water as possible on the plot, the theta probe should be placed at the dryer location within the four inner trees.

Then, the exact middle of the plot should be this place as the probe will be at 61cm from the drippers but as the trees were located at 10 cm from the drippers, the water will be used locally around the trees and only the fraction of water that manages to diffuse into the root zone will participate to the moisture content read at the probe.

It will depend on the probe “teeth” length but the ideal was to have the area screened by the probe at 10 cm depth. This depth was chosen as the capacity of irrigated water to reach the root zone will depend on the capacity of this water to infiltrate this first layer of soil (0-10 cm); where there were fewer roots.

Salinity (EC and Na concentration) has to be monitored as it will influence Theta-probe readings.

6.4.2 DIVINER reading on 170 cm profile on each plot

To assess water consumption, storage and water dynamics in the soil, water content within soil profile was necessary. For this purpose, a DIVINER (DIVINER 2000, Sentek sensor technology) access tube was installed to a depth of 1.70 m on each of the 24 plots. (Figure 16)

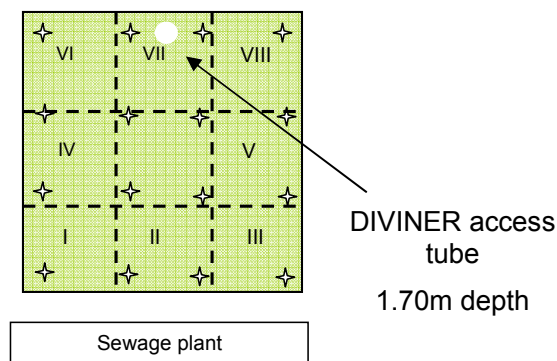


Figure 16 localisation of the DIVINER hole on each plot

The DIVINER probe was calibrated (Groves and Rose, 2004) before use at the beginning of the experiment. As for theta probe, salinity has to be monitored.

⁷ AAS: Atomic Absorption Spectrophotometer

7. STATISTICAL ANALYSIS MODEL

7.1 GENERAL LINEAR MODEL, FACTORS DESCRIPTION

The objective of the statistical analysis of the data collected was to assess any significant effect of a WR system first on wastewater polishing at 30 cm and 60 cm depth, second on any significant effect of a WR system on biomass production, with an interspecies comparison and third, any significant effect of a WR system on soil chemical composition.

7.1.1 Soil water composition and soil chemical composition

On that account, the following statistical analysis will assess the significance of cover effect (factor with four levels: willow, poplar, eucalyptus or unplanted), irrigation effect (factor with two levels: YES or NO), depth effect (factor with two variants: 30 cm and 60 cm depth) and seasonal effect on first soil water chemical compositions and second on soil chemical composition and determine possible interactions between factor cover, factor Irrigation.

The factors identified and the statistical model adopted, were presented in Table 3. The statistical model was a general linear model with 4 fixed factors: cover, irrigation, depth and date and 2 of these were nested factors. For each cover and Irrigation combination, there was a depth and for each cover, irrigation and depth combination, there was a date. In other words, effects were applied to a variable through factors and their potential significance was assessed.

The linear model can be described by the following equation:

Equation 1 General linear model

$$X = \alpha + \beta_{\text{cover}} + \gamma_{\text{irrigation}} + \gamma\beta_{\text{irrigation*cover}} + \delta_{\text{depth}}(\gamma\beta) + \tau(\delta\gamma\beta) + \varepsilon$$

- X: measurable variable
- α : constant
- β_{Cover} : Factor cover contribution (4 levels)
- $\gamma_{\text{Irrigation}}$: Factor irrigation contribution (2 levels)
- $\gamma\beta_{\text{IrrigationCover}}$: Interaction of cover and Irrigation factors contribution
- $\delta_{\text{Depth}}(\gamma\beta)$: Factor Depth contribution (2 levels)

- $\tau(\delta\gamma\beta)$: Factor Time contribution (24 levels)
- ε : residuals

A parametric Analysis of Variance (ANOVA) will be conducted to determine the significant effects.

The null hypothesis was that the means (under different combination of factors) were equal. Rejecting the null hypothesis means that a statistically significant effect was identified (McBean and Rovers, 1998)

Table 5 Factors and model for the statistical analysis.

	<i>Name</i>	<i>Nature</i>	<i>values</i>
Factors	Plot	Random	24
	Cover, β	Fixed effect	4: eucalyptus, poplar, unplanted, willow
	Irrigation, γ	Fixed effect	2: irrigated IR, non-irrigated NR
	Depth, δ	Split-plot, Nested with Tree and Irrigation	2: 30 cm, 60 cm
	Date, τ	Split-plot, Nested with Tree, Irrigation and Depth	24: from the 22/07/06 till the 16/08/07
Variables, X for soil water composition	NH ₄ (mg-N.L ⁻¹), Total Oxidised Nitrogen (mg-N.L ⁻¹), PO ₄ (mg-P.L ⁻¹), Total Nitrogen (mg-N.L ⁻¹), Total Phosphorus (mg-P.L ⁻¹), Na (mg-Na.L ⁻¹), K (mg-K.L ⁻¹)		
Variables, X for soil nutrients composition	Mineral N (NH ₄ -N and TON-N (mg/kg soil)), Total Nitrogen (mg/kg soil), Total Phosphorus (mg/kg soil), Available or Olsen P (mg/kg of soil), Total K(mg/kg of soil), available K(mg/kg of soil), pH, EC, SAR, extractable Na (mg/kg of soil),		

7.1.2 Groundwater analysis

The following statistical analysis was conducted to assess the possible significant effect of the implementation of a WaterRenew system on groundwater by comparing chemical composition upstream and downstream of the field. Hence the factors considered were the factor provenance (2 levels; upstream, downstream) and the factor date (29 levels). There were 2 sampling points for both upstream and downstream sampling.

Equation 2 General linear model

$$X = \alpha + \beta_{\text{Provenance}} + \tau(\beta) + \varepsilon$$

- X: measurable variable
- α : constant
- $\beta_{\text{Provenance}}$: Factor provenance (2 levels)
- $\tau(\beta)$: Factor Time contribution (29 levels)
- ε : residuals

A parametric Analysis of Variance (ANOVA) was conducted to determine significant effects.

The null hypothesis was that the means (under different combinations of factors) were equal. Rejecting the null hypothesis means that a statistically significant effect was identified (McBean and Rovers, 1998)

7.1.3 Tree growth

The following statistical analysis was conducted to compare the irrigation effect (YES or NO) for plant growth (diameter at 8 cm from ground, stem length and Leaf Area Index, data from august 2006 until august 2007) as well as an interspecies responses comparison.

Equation 3 General linear model

$$X = \alpha + \beta_{\text{Tree}} + \gamma_{\text{Irrigation}} + \gamma\beta_{\text{Irrigation Tree}} + \tau(\gamma\beta) + \varepsilon$$

- X : measurable variable
- α : constant
- β_{Tree} : Factor tree contribution (3 levels)
- $\gamma_{\text{Irrigation}}$: Factor irrigation contribution (2 levels)
- $\gamma\beta_{\text{IrrigationTree}}$: Interaction of Tree and Irrigation factors contribution
- $\delta \tau(\gamma\beta)$: Factor Time contribution (13 levels), it was the lowest level and for this reason, it was nested with Tree and Irrigation
- ε : residuals

A parametric Analysis of Variance (ANOVA) was conducted to determine significant effects.

As the amount of effluent irrigated depends on the cover type, the covariate soil moisture was taken into account in the ANOVA.

The null hypothesis was that the means (under different combinations of factors) were equal. Rejecting the null hypothesis means that a statistically significant effect was identified (McBean and Rovers, 1998).

7.2 GENERAL STEPS TO STATISTICAL ANALYSES

The same method was followed for each of the variables.

Analysis of Variance, ANOVA, was conducted on the raw data. A general linear model was fitted following the statistical model.

Then, analysis of the residuals was conducted as a *sine qua non* condition of that the residuals were normally distributed.

Then, once this condition was satisfied, a general linear model was fitted. Then if there was a statistically significant F test from ANOVA, the results were further investigated in terms of Fisher least significant differences (LSD). Indeed, if a factor was significant for a variable, knowing how the different levels contributed was interesting (Olsen et al., 1954.). The Fisher LSD test was used to determine significant differences between particular levels of the factor. The significance level used was $p < 0.05$.

The means considered were the weighted means. These means take into account the actual number of data points within each mean.

8. CONCLUSION

This chapter described the methodology followed to set up a WaterRenew system field trial and to run it at Cranfield University sewage treatment works (Bedfordshire, UK).

The specific objectives of this field trial were:

- **Objective 1:** To quantify wastewater treatment efficiency by quantifying the main treatment processes for N and P and secondary K and Na and assess the relative importance of each of the compartment soil and plant.
- **Objective 2:** To identify the upper limits for effluent applications before observing either on a chemical point of view, poor nutrient removal efficiency, or hydrological point of view, with permanent ponding or on a physiological point of view with reduced tree yield or health.
- **Objective 3:** To gather data to establish simple equations in order to develop a design and operational tool for WaterRenew systems.

The field trial was established in September 2005 and constituted of 24 plots, randomly distributed and fully replicated. 3 species of trees, willow, poplar and eucalyptus were planted and compared to unplanted plots irrigated with secondary treated wastewater and non-irrigated. Soil quality was monitored every year in February, tree growth was monitored monthly, tree nutrients contents yearly and soil water quality was monitored fortnightly during the whole experiment. Each compartments, soil, soil water and trees will be studied in the following chapters. (Figure 17)

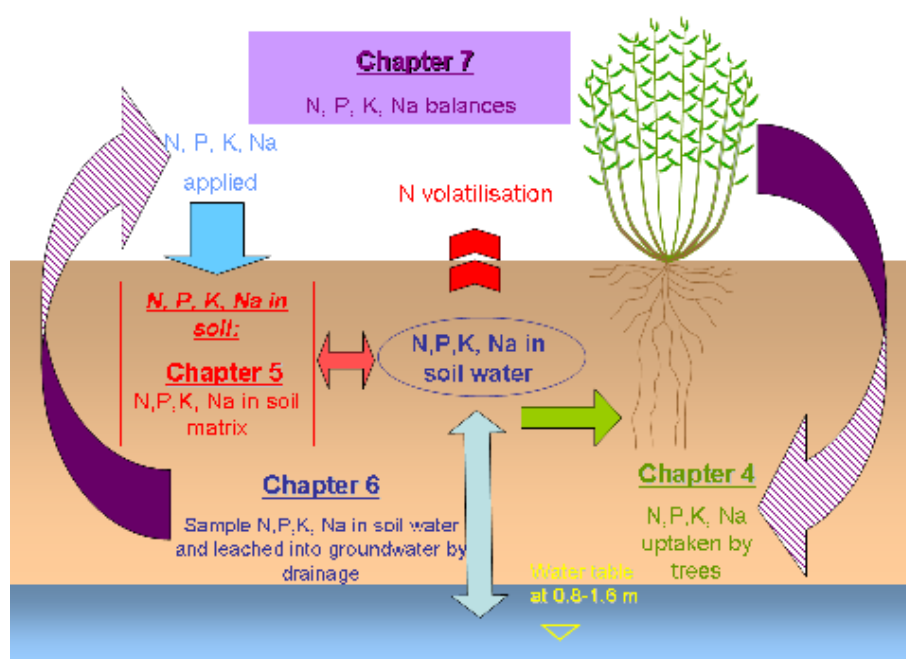


Figure 17 Thesis outline with nutrients (N, P, K, and Na) fate and interactions between the different compartments of a WaterRenew system (soil, soil water, plant).

9. REFERENCES

- Allen, R. G. (1998.), *Crop evapotranspiration: guidelines for computing crop water requirements*, Food and Agriculture Organization of the United Nations, Rome.
- Avery, B. W. (1980), "Soil Classification for England and Wales (Higher Categories)", *Soil Survey technical Monograph*, vol. 14.
- Avery, B. W. (1973), "Soil Classification for England and Wales.", *Journal of Soil Science*, vol. 24, pp. 324-338.
- Avery, B. W. and Bascomb, C. L. (1982), "Soil survey laboratory methods: chapter 4. Density and Water release characteristics.", *Soil Survey*, , pp. 42-56.
- Avery, B. W., Bascomb, C. L., Soil Survey of England and Wales. and Hill, M. N. (1974.), *Soil survey laboratory methods*, Rothamsted Experimental Station, Lawes Agricultural Trust, Harpenden.
- Breuer, L., Eckhardt, K. and Frede, H. (2003), "Plant parameter values for models in temperate climates", *Ecological Modelling*, vol. 169, no. 2-3, pp. 237-293.
- Clayden, B. and Hollis, J. M. (1984), "Criteria for Differentiating Soil Series.", *Soil Survey, Technical Monograph*, vol. 14.
- DEFRA (c2002.), *Sewage treatment in the UK: UK implementation of the EC Urban Waste Water Treatment Directive: sensitive areas : September 2002*, Department for Environment, Food & Rural Affairs, London.

- DEFRA (2002.), *Growing short rotation coppice: best practice guidelines for applicants to DEFRA's energy crops scheme*. DEFRA, London.
- DEFRA (2002a), "Guidelines for Farmers in NVZs – England.", vol. PB5505.
- DEFRA (2002b), *Implementation of the Nitrates Directive (91/676/EEC), Description of the methodology applied by the Secretary of State in identifying additional Nitrate Vulnerable Zones in England*. Water Quality Division, 1.
- Ehlers, W. and Goss, M. (. (2003), "Water Dynamics in Plant Production.", *Wallingford: CABI Publishing.*, , pp. 273 pp.
- FAO (1985), *Guidelines: Land Evaluation for Irrigated Agriculture*. 55, FAO Soils Bulletin, FAO, Rome.
- GB, Parliament. Joint Committee on Statutory Instruments. (2008), *Action Programme for Nitrate Vulnerable Zones (England and Wales) Regulations 2008*. Great Britain. Parliament. House of Commons.; Great Britain. Parliament. House of Lords.(draft for consultation), The Stationery Office.
- Hall, D. G. M., Reeve, M. J., Thomasson, A. J. and Wright, V. F. (1977), "Water Retention, Porosity and Density of Field Soils", *Soil Survey Technical Monograph No 9.*, vol. Harpenden: Soil Survey, pp. 19-20.
- Hillel, D. (1980), *Applications of Soil Physics*. Academic Press.
- MAFF, (2000), *Fertiliser recommendations for agricultural and horticultural crops (RB209)*, Seventh edition ed., the stationary office, London, UK.
- MAFF (1986.), *The analysis of agricultural materials: a manual of the analytical methods used by the Agricultural Development and Advisory Service*, 3rd ed, HMSO, London.
- Olsen, S. R., Cole, C. V., Watanabe, F. S. and Dean, L. A. (1954.), "Estimation of available phosphorus in soils by extraction with sodium bicarbonate. ", *USDA*, vol. Circular 93., pp. 1-19.
- Reeve, R. C., Luthin, J. N. and Donnan, W. W. (1957), "Drainage investigation methods. Drainage of Agriculture Lands", , pp. 395-459.
- Richards, L. A. and Allison, L. E. (1954.), *Diagnosis and improvement of saline and alkali soils*, U.S. Government Printing Office, Washington, D.C.
- Schoumans, O. F., W. de Vries, W. and Breeuwsma, A. 1. (1986), "A phosphate transport model for application on regional scale.", *Winand Staring Centre for Integrated Land, Soil and Water Research, Wageningen, The Netherlands (in Soil Survey series).*, vol. 1951.
- Scott, C. A., Zarazúa, A. J. and Levine, G. (2000), "Urban-Wastewater Reuse for Crop Production in the Water-Short Guanajuato River Basin, Mexico.", *IIMI Research Report*, vol. 41.
- Spangenberg, A. and Kolling, C. (2004), "Nitrogen Deposition and Nitrate Leaching at Forest Edges Exposed to High Ammonia Emissions in Southern Bavaria", *Water, Air, & Soil Pollution*, vol. Volume 152, no. 1, pp. 233-255.

- Tabbush, P. M., Parfitt, R. and Tubby, I. ((Revised, in press)), "Poplar and willow varieties for short rotation coppice.", *Forestry Commission Information Note 17.*, vol. 17.
- Trindade, H., Coutinho, J., Van Beusichem, M. L., Scholefield, D. and Moreira, N. (1997), "Nitrate leaching from sandy loam soils under a double-cropping forage system estimated from suction-probe measurements", *Plant and Soil*, vol. 195, no. 2, pp. 247-256.
- Weatherhead, E. K. and Knox, J. W. (2000), "Predicting and mapping the future demand for irrigation water in England and Wales", *Agricultural Water Management*, vol. 43, no. 2, pp. 203-218.

CHAPTER 4 : GROWTH AND WATER USE OF SALIX VIMINALIS, POPULUS TRICHOBEL AND EUCALYPTUS GUNNII FIELD TRIAL PLANTATION IRRIGATED WITH SECONDARY TREATED EFFLUENT

1. INTRODUCTION

Chapter 3 described both the field experiment setup and the monitoring settings at Cranfield University in order to quantify, with the main aim of the Water Renew project itself, i.e. to couple in the best way, wastewater management with renewable energy production, and to study how potentially problematic components in wastewater; nutrients, can be recovered from the wastewater to fertilise short rotation coppice (SRC).

A SRC is defined as a coppice “densely planted, high-yielding varieties of either willow or poplar, harvested on a 2– 5 year cycle, although commonly every 3 years” (DEFRA, 2002.). SRC as biomass produces are currently contributing to 2.3 % of UK electricity generation, but to meet renewable energy targets, biomass should provide nearly 30 % of the UK’s energy and heat generation (BERR, 2008) and in particular, according to BERR consultancy report (2008), “the proportion of biomass combusted derived from crops planted after 1989 for bio fuel production must be 25 % in the year commencing April 2009. This proportion must increase to 50 % in the year commencing April 2010, and to 75 % in the years from April 2011 - March 2016” (BERR, 2008).

This chapter will focus on presenting the tree response to irrigation with secondary treated effluent with application maintaining the first 10 cm of soil to field capacity. The field trial was set up in Cranfield University in September 2005 (Figure 1). The specific objectives of this chapter are the following:

- **Objective 1:** focused on SRC mass productions in a WaterRenew system:
 - 1) Quantifying yield performance evolution (seasonal effect, irrigation effect).
 - 2) As effluents contain Na, assessing if any sign of stress can be identified regarding Na stress.
 - 3) Quantifying and comparing yields between tree species to identify species related effects.

- **Objective 2:** focused on SRC water-use in a WaterRenew system:
 - 1) Quantifying water-use evolutions (seasonal effect, irrigation effect).
 - 2) Quantifying and comparing water-use between tree species to identify species effect,
- **Objective 3:** focused on SRC nutrient uptake in a WaterRenew system:
 - 1) Quantifying nutrient uptake evolutions (seasonal effect, irrigation effect).
 - 2) Quantifying and comparing nutrient uptake between tree species to identify species effect,

2. METHODS

2.1 SITE AND STAND DESCRIPTION

The plantation was established in March-April 2006 adjacent to the Cranfield university sewage treatment works in Cranfield, Bedfordshire, UK. *E. gunnii*, E, were planted in October 2005 at a height of 60 cm and dead trees, 50 % of the original plantation on each plot, were replaced in April 2006,. *S. viminalis*, W, and *P. trichocarpa*, P, were planted from stems collected in March 2006 before blossoming, cut to a length of 20 cm and buried for 19 cm in March 2006 according to (DEFRA, 2002.). Usually, at the end of the first year, mono-stems are cut back to promote sprouting (Aronsson et al., 2000). In order to mimic this second year cut back poplars and willows were planted as a cluster of five cuttings in spring 2006 and buried to show 1 cm above ground. All trees were planted at one meter spacing, at a density of 13060 tree.ha⁻¹, an intermediate density for SRC, (DEFRA, 2002) on a total field area of 22 mx22 m. This density is a very high density for eucalyptus, almost 3 times more than highest density reported in the literature (Myers B.J. et al., 1996). Unplanted plots were also prepared (U, unplanted).

The mean annual rainfall at the site is 629 mm, 10.0 °C mean annual temperature and an annual average Penman evapotranspiration of 1.4 mm.day⁻¹ (Cranfield University, Silsoe Met Station, data from 1992-2006).

The field was artificially built and soil completely disturbed. The cover was pasture with regular grass cutting as only treatment.

2.2 EXPERIMENTAL DESIGN AND TREATMENTS, FIELD WORK

Legend:

- U** Unplanted
- E** Eucalyptus
- W** Willow
- P** Poplar
- +** = irrigated
- = non-irrigated
- = borehole

Flow Direction: Discharge river (with flow direction) →

Outfall from underground pipe

Plot Arrangement (4 rows by 5 columns):

Row	Col 1	Col 2	Col 3	Col 4	Col 5
1	U+	W-	P+	U-	P-
2	U-	P+	E+	E-	W+
3	E+	P-	U-	E-	P+
4	W-	U+	E-	W+	P-

Plot Numbers:

Row	Col 1	Col 2	Col 3	Col 4	Col 5
1	1	2	3	4	5
2	6	7	8	9	10
3	11	12	13	14	15
4	16	17	18	19	20

Additional Plots:

Row	Col 1	Col 2	Col 3	Col 4
5	W+	W-	E+	U+
6	21	22	23	24

4-3

The rate of effluent irrigation is based on the water-use rates of the different trees in response to the climate and canopy development. A computerised drip-irrigation system (Campbell data logger) was set up, with 16 pressurised drippers ($4 \text{ L}\cdot\text{hour}^{-1}$, *pressure compensating, Woodpecker Dripper, UK*) per plot to control the irrigation. The numbers of drippers per plot was doubled in January 2007 increasing the irrigation capacity from $15.4 \text{ mm}\cdot\text{day}^{-1}$ to $30.8 \text{ mm}\cdot\text{day}^{-1}$. The same drippers were installed. The irrigation system was able to operate from 6 am to 6 pm in aggregate and a maximum of 3 hours per day per plots with the same cover.

The main idea of the irrigation system settings was to allow the maximum water application constrained by no or minimum runoff, minimising drainage and consequently creating well watered favourable conditions for plant growth from July 2006 until December 2007. For this reason, the irrigation was triggered by soil moisture measurements (soil moisture sensor SM200, Delta T) in the middle of each plot to start application when soil moisture content was lower than field capacity (0.55 and this latest was determined by pressure membrane method on undisturbed soil samples collected on the surface of each plot, Chapter 3, 5.2). The irrigation started in mid-July 2006 until late December 2006. Then, it was stopped due to water freezing in the pipe-work until late February 2007 and set back on March 2007 until October 2007. Then, at the end of the experiment, the irrigation system was forced, from October 2007 until February 2008, by switching it on manually for an hour per day per plot until stress signs on trees were observed. To detect the impact of the trial on groundwater, boreholes were set upstream and downstream of the plots and water samples taken fortnightly.

The effluent used is a secondary treated sewage meeting UK regulations for discharge quality. Its analysis according to FAO 29 (1985) classifies its use restriction for irrigation as none to slight. The effluent was slightly alkaline (average pH of 7.2 ± 0.5 on samples for 2005-2006-2007 collected weekly) and contained moderate concentrations of nutrients (average concentrations of $29.8\pm4.8 \text{ mg}\cdot\text{N}\cdot\text{L}^{-1}$, $3.2\pm2.1 \text{ mg}\cdot\text{P}\cdot\text{L}^{-1}$ and $20.0\pm11.0 \text{ mg}\cdot\text{K}\cdot\text{L}^{-1}$). (Details on soil water, groundwater and effluent chemistry are in Chapter 7, 3.1-3.5)

2.3 GROWTH MEASUREMENTS

The height, diameter at 8cm from ground (diam8cm) and leaf area index (LAI with Sunscan, Delta T Image Analysis System, Delta T Devices Ltd., Cambridge, UK) were

measured monthly from July 2006 to February 2008 on the four central trees on each plot. The 12 others were considered as a buffer for irrigation and/or different species tree proximity (Chapter 3, 5.4).

In October 2006, leaves were sampled from each plot for leaf mass production and nutrient content analysis. In July 2007, selected stems were harvested on each plot for biomass analysis (dry weight and nutrient content for leaves).

Stems were chosen to cover the range of observed diameters for each species and irrigation regimes and separated into foliage and stem (wood). Fresh weight and dry weight for both leaf and wood were recorded. Then, leaf samples were left to dry at 50°C for 48 hours following proceedings from RB 427 (MAFF, 1986.). Wood samples were left to dry at 105°C until dry weight stabilised (MAFF, 1986.).

Because of greater incertitude in stem height measurements, allometric relationships were derived based on 9 measurements of diameter at 8 cm from ground for each tree species irrigated or not by linear regression.

These equations (Equation 1) were used to estimate the total foliar biomass for both 2006 and 2008 and wood mass for July 2007 and nutrient content of that component for the plantation (Myers B.J. et al., 1996). However, dry wood mass was calculated from fresh stem weight at harvest in February 2008 and water content determined on subsamples from each plot.

$$\begin{aligned} (1) \text{ biomass_wood (g)} &= f(\text{diameter_mm}) \\ (2) \text{ cumulative_biomass_leaf (g)} &= f(\text{diameter_mm}) \end{aligned} \quad \text{Equation 1}$$

2.4 WATER-USE ESTIMATES

Seasonal water balance was calculated for non-irrigated and irrigated plots under the different covers by solving Equation 2. The bottom limit of the hydrological system was set to 60 cm depth.

One of the sources of nutrient loss is in soil water when soil water drained out of the system. Therefore, the next step to assess nutrients balance is to calculate a water balance. Therefore, the different elements of the water balance equation (Equation 2, Allen, 1998) need to be assessed.

Equation 2 Soil water balance and assumptions

$$ET = \text{Irrigation} + \text{Rain fall} - \text{Runoff} - \text{Drainage} + \text{Capillary Rise} \\ \pm \Delta \text{Subsurface Flow} \pm \Delta \text{Soil Water Storage}$$

Assumptions :

- 1) $ET = \text{Evapotranspiration}$
- 2) $\text{Runoff} = 0$ (controlled with the polythene sheet)
- 3) $\text{Capillary Rise} = 0$ $\left(\begin{array}{l} \text{because of lower PSMD}^1 \text{ during} \\ \text{period of experiment compared to average} \end{array} \right)$
- 4) $\text{Subsurface Flow} = 0$ (controlled with the polythene sheet)
- 5) $\text{Soil Water Storage} = \text{soil water storage from 0cm to 60cm}$

Hence

$$\text{Drainage} = \text{Irrigation} + \text{Rainfall} - ET \pm \Delta \text{Soil Water Storage}$$

To go back to Equation 2, water balance for Cranfield site was simplified with the following assumptions:

- A polythene sheet of 60 cm was buried for 50 cm to hydrologically and physically individualise each plot for 2 purposes: to prevent subsurface flows and lateral flows on the first 50 cm depth and secondly, with the 10 cm sheet above ground, to prevent surface runoff.
- Capillary rise depends mainly on ET (Hillel, 1980). For the period of experimentation, July 2006 to February 2008, the average annual PSMD from data collected from 1962 to 2007, was of 1246 ± 79 mm. The average annual PSMD for 2006 and 2007 were respectively 1166 ± 82 mm and 769 ± 44 mm. Therefore, for 2006, PSMD is the 40 years average but 2007 is significantly lower. Moreover, on irrigated plots, irrigation was maintaining soil moisture at or close to field capacity, which would have limited water movement in that layer. Hence, even though the water table was high (between 0.8 m-1.6 m) capillary rise was considered as limited and not accounted further more.

Rainfall and evapotranspiration were measured locally and data are available from Silsoe campus (Cranfield University) automatic meteorological station. Irrigation was also measured on site, hence data are available.

¹ PSMD: potential soil moisture deficit (mm)

Soil water storage from 0 cm to 60 cm depth was calculated from soil water contents measured with a capacitance probe (DIVINER2000 utilising Frequency Domain Reflectometry (FDR), Sentek sensor technologies, Australia) almost every month during the irrigation period (March to October in 2006 and 2007).

Measures were taken every 10 cm until 1.60 m depth but the system was limited to 60 cm for two reasons, first because the eucalypts, willow and poplar root system maximum density zone is around 10-20 cm. Studies confirmed that the majority of willow roots are located in the top 10-20 cm of the soil (Volk et al., 2001; Ehlers and Goss, 2003; Elowson and Rytter, 1984). Poplars have roots a little deeper but remain superficial with more than 50 % of fine root biomass of hybrid poplar in the soil to a depth of 3.1 m was found in the first 36 cm of soil (Heilman et al., 1994; Crow and Houston, 2004). For eucalyptus (*E.nitens*), Moroni et al 2002, found that more than 50 % of the root mass densities were located between 10 and 20 cm depth, both in irrigated or drought stressed conditions. Second because the water table was between 50 cm to 70 cm depth.

The field got flooded in January 2007 and October 2007 and soil moisture content was measured more closely around the flooding episodes to assess drainage rate at different soil moisture contents at 60 cm depth.

As each plot was isolated with a 60 cm width polythene sheet buried for 50 cm and showed 10 cm on surface, apart from these two flooding episodes, surface runoff was contained on each plot. Consequently, the main mechanism for water loss, other than evapotranspiration, was drainage.

In this chapter, the interest is focused on the tree response to treated wastewater irrigation. Moreover, ET, evapotranspiration is defined as “the combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration” (Allen, 1998.):

$$ET = Tr + Ev$$

Definition

ET : Evapotranspiration ($mm.day^{-1}$)

Equation 3

Tr : amount of water transpired by crop ($mm.day^{-1}$)

Ev : amount of water evapored by soil surface ($mm.day^{-1}$)

The transpiration part of ET was identified as water use. Therefore, on considering Equation 1 for both planted and unplanted plots, water uses of different species were assessed as:

$$\Delta \text{Drainage}_{\text{Tree-Unplanted}} = \Delta \text{Irrigation}_{\text{Tree-Unplanted}} + \Delta \text{ET}_{\text{Tree-Unplanted}} \\ \pm \Delta \text{Soil Water Storage}_{\text{Tree-Unplanted}}$$

with the simplifications

$$\begin{cases} \text{simplification 1 : } \Delta \text{Drainage}_{\text{Tree-Unplanted}} \approx 0 \\ \text{simplification 2 : } \Delta \text{Soil Water Storage}_{\text{Tree-Unplanted}} \approx 0 \end{cases}$$

Equation 4

hence

$$\text{Water Use} = \text{Tr} = \Delta \text{Irrigation}_{\text{Tree-Unplanted}}$$

Simplifications 1 and 2 arose from the same assumption based on the fact that once the Cranfield site was hydrologically equilibrated, as Cranfield site irrigation system was set to maintain soil moistures to a certain and same threshold for all plots, field capacity, drained amount and variations of soil water storage could be considered as equal under any cover.

These simplifications can be justified as hydraulic conductivity and soil moisture variations should be the same. Firstly, soil can be considered homogeneous under every plot as the field was artificially built up with the same soil and they will all present the same water release curve. Secondly, as the same soil moisture was maintained under all irrigated plots at surface, hydraulic conductivity would have been similar because hydraulic conductivity depends directly on soil moisture (Hillel, 1980). Third, as all the plots were located at the same place and under the same climatic conditions, soil moisture changes will be the same as well. For these reasons, drained volumes would be the same when calculated with Darcy's law, (Equation 5) (Hillel, 1980; Darcy, 1856).

Equation 5 : Darcy's law

$$q = -K_h * \text{grad}(h)$$

$$q : \text{flux } (m^3 . h^{-1})$$

$$K_h : \text{hydraulic conductivity } (m.h^{-1})$$

$$h : \text{water head } (m)$$

However, the main condition for these simplifications is the hydrological equilibrium of the system. As the experiment started in July 2006, when usually soil is in deficit of field capacity (Stephens et al., 2001a) from the end of March for Bedfordshire. At the beginning, a period of equilibration of the system would have taken place where soil moisture was wetted up to field capacity.

2.5 CROP FACTOR

Crop factor is defined in FAO 56 (Allen, 1998.) as the ratio between crop evapotranspiration and reference evapotranspiration:

Equation 6 : Steps to calculate K_c

$$ET_c = K_c * ET_0$$

with

ET_c : crop evapotranspiration

ET_0 : reference evapotranspiration measured by the automated
met station in Silsoe

hence

$$\left\{ \begin{array}{l} K_c = \frac{ET_c}{ET_0} \\ ET_c = Tr + Ev \\ Ev \approx ET_0 \\ Tr = \Delta Irrigation_{Tree-Unplanted} \end{array} \right. \Leftrightarrow K_c = \frac{\Delta Irrigation_{Tree-Unplanted} + ET_0}{ET_0}$$

Hence, K_c calculation was conducted with the approximation of evaporation, Ev , by reference evapotranspiration ET_0 . This will lead to an overestimation of K_c as ET_0 represents evapotranspiration from a well watered homogeneous grass surface (Allen, 1998.). However, it was judged as the best guess according to the data set available.

Stephens et al. (2001b) reported K_c was deeply influenced not only by the height of vegetation but also by width of vegetation. They present the following formula to estimate appropriately K_c :

$$K_c = \min\left(1.2 + \frac{F_r * h_{canopy}}{width}, 2.5\right)$$

where

F_r : stomatal resistance correction factor **Equation 7**

h_{canopy} : mean vertical height of canopy area (m)

width : width, horizontal thickness of vegetation (m)

Stephens et al. (2001b) reported that when plots are small (<10 m), then more advective energy from dry ground around plots can contribute to evapotranspiration, therefore these plots' trees can present $K_c > 1$ however, an upper limit of 2.5 had to be imposed to "represent the maximum stomatal capacity of the vegetation to supply water vapour to the air stream under advective conditions".

Equation 7 was arranged:

$$K_c = \min\left(\frac{Tr + ET_0}{ET_0}, 2.5\right) \quad \text{Equation 8}$$

Interception was not calculated and assumed to be negligible as canopy closure was not reached.

LAI data were plotted on the K_c s graphs because Allen (1998) relates K_c to LAI (Allen, 1998.). However it is not a linear equation:

$$K_{c_{basal_mid}} = K_{c_{min}} + (K_{c_{basal_full}} - K_{c_{min}})(1 - \exp[-0.7 * LAI])$$

2.6 FOLIAR AND WOOD NUTRIENTS

In October 2006 and summer-autumn 2007, leaves were sampled. For aboveground woody biomass, there was one sampling in October 2006 and one in February 2008 at the end of the growing season and after trees had shed their leaves. For each plot, 3 stems were chosen to cover the range of present diameters and fresh biomass was weighed and all the sampled whole stems were dried and shred for analysis. All the leaves present on the selected stems were removed and dried at 100°C for 18 hours (MAFF, 1986.) to determine their moisture content and for chemical analysis. Total Nitrogen and Total Carbon contents were determined by Elementar Vario EL

(Elementar Analyser systeme GmbH, Hanau, Germany), total phosphorus and total potassium contents were determined on acid digested biomass (hypochloric and nitric acid; aqua regia, (MAFF, 1986.) by, respectively, flame photometry and ammonium molybdate colorimetric method.

2.7 STATISTICAL ANALYSIS

A parametric Analysis of Variance (ANOVA on General Linear Model, with STATISTICA 8.0, Statsoft) was conducted to determine significant differences in comparison of variances allocated to a tree species factor, irrigation factor, an interaction between tree and irrigation factor and a date factor recorded evolution of the stands in time. LSD (least significant difference) of 5 % was considered. (Details in Chapter 3, 7.1.3).

Equation 9 General linear model

$$X = \alpha + \beta_{Tree} + \gamma_{Irrigation} + \gamma\beta_{Irrigation\ Tree} + \tau(\gamma\beta) + \varepsilon$$

- X: measurable variable
- α : constant
- β_{Tree} : Factor tree contribution (3 levels)
- $\gamma_{Irrigation}$: Factor irrigation contribution (2 levels)
- $\gamma\beta_{IrrigationTree}$: Interaction of Tree and Irrigation factors contribution
- $\delta \tau(\gamma\beta)$: Factor Time contribution (13 levels), it is the lowest level and for this reason, it is nested with Tree and Irrigation
- ε : residuals

2.8 WATER AND NUTRIENT USE EFFICIENCIES

2.8.1 Water use efficiency

Water use efficiencies defined by Equation 10 (van Wijk et al., 2003) were calculated for each tree.

Equation 10 (van Wijk et al., 2003).

$$\text{With define as followed: } WUE = \frac{\text{dry matter production (g)}}{\text{water loss (kg)}}$$

- *dry matter production:*
 - *total crop*
 - *above ground crop*
 - *only leaves*
- *water loss:*
 - *transpiration*
 - *or transpiration + soil evaporation*
 - *or transpiration + soil evaporation + interception loss*

The definition chosen was:

$$WUE = \frac{\text{above ground crop (g)}}{\text{Transpiration (kg)}} \quad \text{Equation 11}$$

– *above ground crop* : leaf + wood
– *Transpiration* = $\Delta \text{Irrigation}_{\text{Tree-Unplanted}}$

Therefore with this definition, WUE represents the amount of water needed to be transpired to produce a certain amount of above ground biomass.

2.8.2 Nutrient use efficiency

Nutrient use efficiency (NUE) is defined by Equation 12; i.e. the mass of biomass produced by mass of a particular nutrient (van Wijk et al., 2003).

$$NUE = \frac{\text{mass of dry matter (g)}}{\text{mass of nutrient (g)}} \quad \text{Equation 12}$$

Average nutrient removals were calculated as the amount of nutrient constituting tree biomass. Because willow and poplar lose their leaves in autumn unlike eucalyptus, nutrients' use efficiencies were calculated for wood biomass and nutrients' content (willow, poplar and eucalyptus, irrigated or not).

3. RESULTS AND DISCUSSION

3.1 CLIMATE

The experiment started with the irrigation switched on from the 14/07/06 until the 11/02/08 with the irrigation system shut down, from November 2006 until March 2007 to avoid frost related damages in the system. Hence, weather during these 2.5 years was compared to 30 years averaged calculated from data collected at Silsoe Automatic meteorological station.

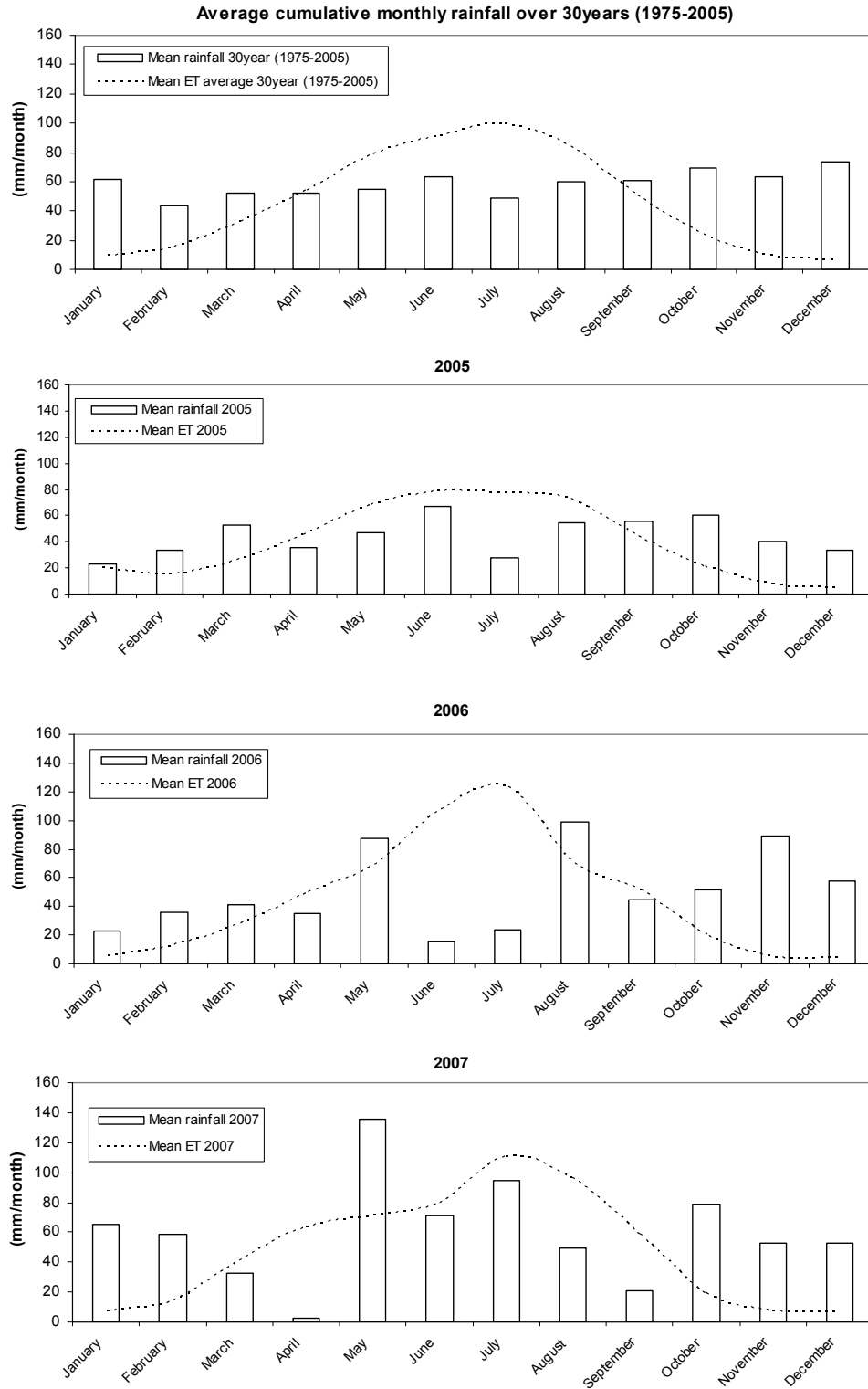


Figure 2 Mean monthly rainfall in $\text{mm}\cdot\text{month}^{-1}$ (bars) and FAO Penman-Monteith reference evapotranspiration (---) in mm over 30 years (1975-2005) and in 2005, 2006, and 2007.

Potential soil moisture deficit (PSMD) is defined as “the quantity of water from rainfall or irrigation needed to return a soil to field capacity i.e. the maximum water holding capacity when free drainage can occur” (Kettlewell et al., 2003). Hence, PSMD represents the amount irrigable for our settings. Compared to the 30 years average, the 3 years while the experiment took place, 2005, 2006 and 2007, were very wet years, hence low PSMD, 2005 presented 25 % of PSMD, 2006, 41 % and 2007 28 % of the 30 years average.

Thus in terms of our WaterRenew field trial, as irrigation was triggered by soil moisture deficit to field capacity, the meteorological conditions of 2006 and 2007 were not optimum in the sense that the PSMD for these years was significantly lower than the 30 year average, hence, less effluent could be effectively applied and the system was not pushed to its limits naturally.

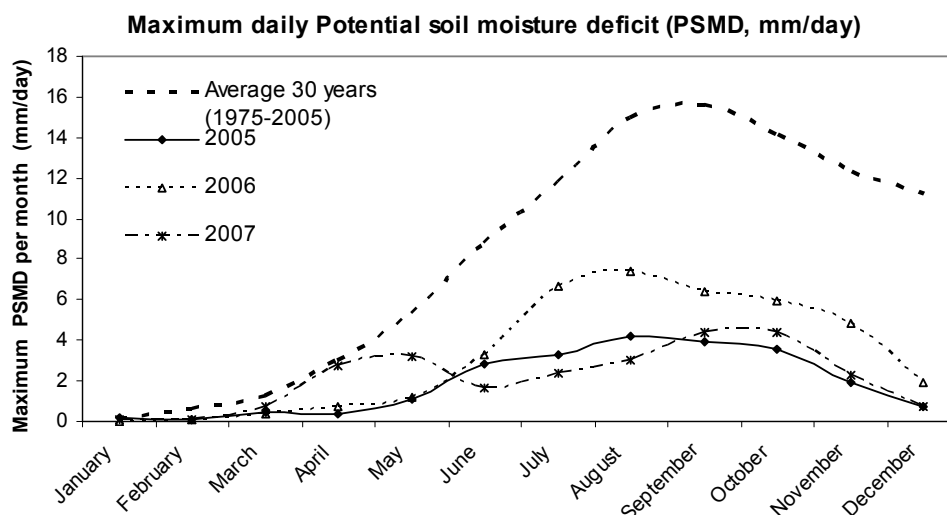


Figure 3 Potential soil moisture deficit ($\text{mm}\cdot\text{day}^{-1}$) (PSMD), average over 30 years (1975-2005), in 2005, 2006 and 2007.

As the system could not be pushed because of limited irrigable volumes, irrigation was turned on manually during winter 2007-2008 to monitor the effect of intensive irrigation during the winter, supposedly the worst period for fertigation with the highest risk of direct leaching of irrigated effluent into groundwater, as plant activity is very low, therefore uptakes are also low.

3.2 STAND GROWTH

3.2.1 Stem length

For ANOVA relevance, residuals need to follow a normal distribution (McBean and Rovers, 1998) (details in Chapter 3, 4, 4.1.2) and it was verified for stem length data.

Table 1 ANOVA table for stem length from both irrigated and non-irrigated eucalyptus, poplar and willow (in bold, significant factors, $p < 0.05$)

	<i>Degree of - Freedom</i>	<i>Stem length (m) - F</i>	<i>Stem length (m) - p</i>
Intercept	1	5594.56	0.00
Date(Tree*Irrigation)	96	58.95	0.00
Tree	3	326.78	0.00
Irrigation	1	6.30	0.01
Tree*Irrigation	3	6.20	0.00
Error	4364		
Total	4467		

Irrigation increased stem length significantly and there was no adverse effect of irrigation. On the contrary, stems on irrigated plots were taller than on non-irrigated plots for the 3 tree species. However, even though the positive effect of irrigation with effluent was significant from August 2006 until February 2008 for poplar, it was significant only at two dates on July 2007 and February 2008 for willow and, never significant for eucalyptus.

Willow and eucalyptus stem lengths were significantly higher than poplar stem length for the whole period of trial for both irrigated and non-irrigated plots. Eucalyptus stems were significantly taller until August 2006, then willow stems became significantly taller from July 2007; i.e. the second growing season. (Figure 4)

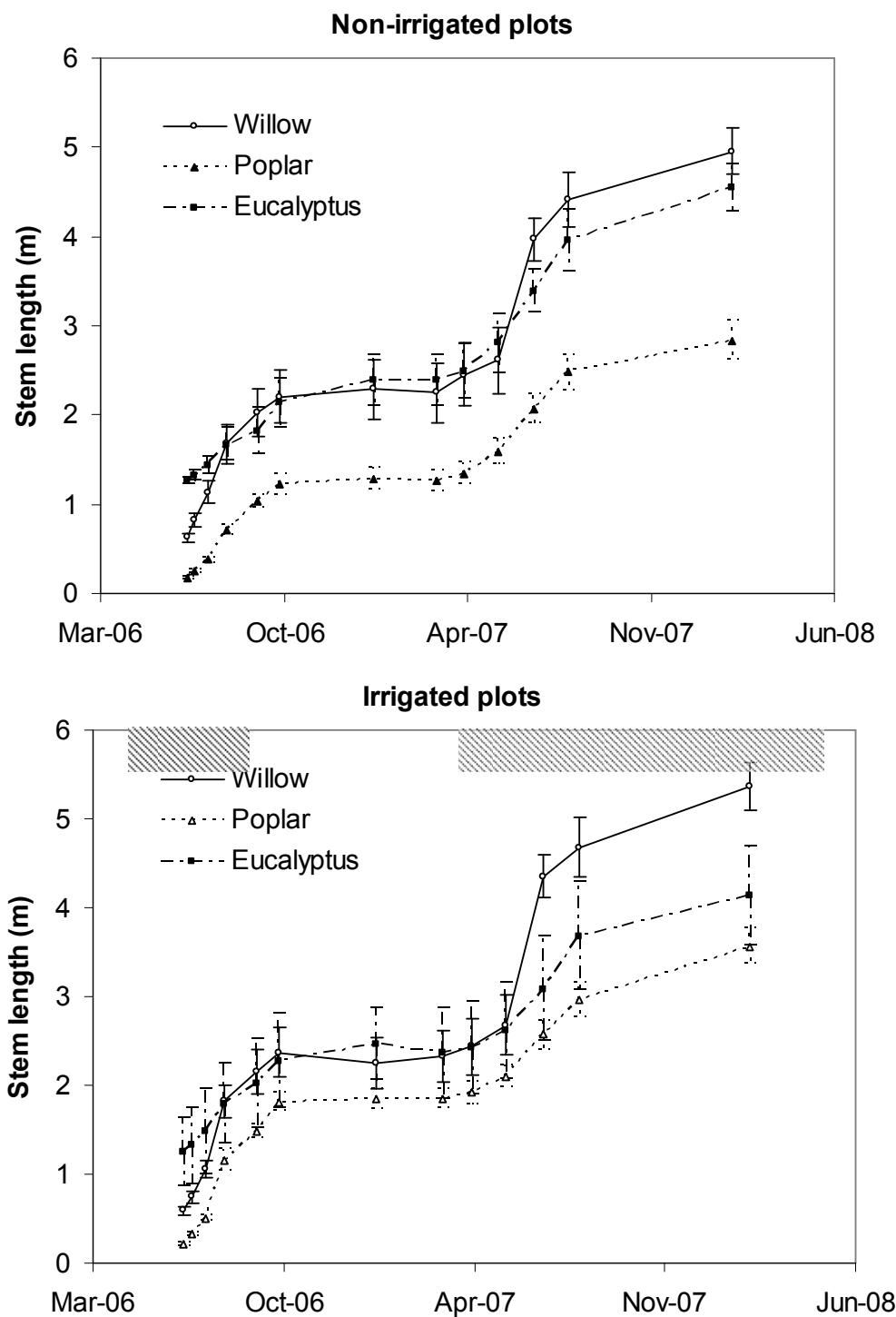


Figure 4 Evolution of stem height (m) from July 2006 until February 2008 of *S. viminalis*, *P. trichocarpa* and *E. gunnii* stands irrigated with secondary treated effluent or not irrigated for 32 months. (Dashed zones indicate the periods of irrigation and vertical bars denote 0.95 confidence interval.)

There was more variability for eucalyptus than for willow and poplar. This can be explained by the fact half of eucalyptus trees had to be replanted in March 2006 as they were initially planted in October 2005. The patterns were the same for both irrigated and non-irrigated plots in terms of growing rates.

Thus, for all tree species, there was first a period of fast growing from July 2006 until October 2006, then, a winter dormancy period from October 2006 until April 2007 and third a fast growing period from April 2007 until November 2007. For both growing seasons, willow trees were presenting steeper slope, therefore faster growing rate than poplar and eucalyptus. Indeed, eucalyptus and poplar trees were presenting comparable growth rates as the slopes of their stem lengths evolutions were comparable and their curves parallel. Irrigation only increased growth rates but did not change patterns, willow trees grow faster than poplar and eucalyptus trees, irrigated or not.

3.2.2 Foliar and woody biomass

3.2.2.1 Establishment of allometric relationship to calculate biomass yield

Linear and non-linear regressions were fitted on data of diameter measurements and corresponding stems dry mass. They were established by tree species and by irrigation. The relationships established are presented in Table 2 and 3.

For leaf biomass linear regression, there were two sets of data available, and therefore, there was one regression derived from leaf biomass measurements in July 2007 and a second one deriving from leaf biomass measurements in October 2007, when leaves were already yellowing for willow and poplar.

For wood biomass, the set of wood biomass measurements collected in February 2008 were used. Usually non-linear regressions (power law, Equation 13 (b)) are developed in the literature (Castelan-Estrada et al, 20001, Kirui et al, 2006). However, the non-linear regression provided unrealistically high yields. For this reason, another model was fitted; a linear regression. To decide whether non-linear or linear regression was better, another approach was taken. While sampling wood biomass, every stem's fresh weights were recorded. However, to assess oven dry wood biomass, only a subsample of stems was effectively dried. Therefore, the total oven dry wood biomass was assessed by using wet weights and wood moisture contents.

- (1) $biomass_wood (g) = a * (diameter_mm) , R^2$
 (2) $cumulative_biomass_leaf (g) = a * (diameter_mm) , R^2$ **(a) Equation 13**

The power version of allometric relationships for wood

$$biomass_wood (g) = a * (diameter_mm)^b , R^2 (b)$$

Table 2 Allometric relationship or linear regression coefficient between leaf biomass and stem diameter measured at 8 cm in mm from ground. ($y=a*x$, a: slope, R^2 : coefficient of determination)

Cumulative Leaf biomass	Jul-07			Oct-07	
	Irrigation	slope	R^2	slope	R^2
Eucalyptus	Irrigated	4.25	0.85	3.76	0.81
Eucalyptus	Non-irrigated	6.47	0.89	5.26	0.76
Poplar	Irrigated	2.72	0.67	2.59	0.82
Poplar	Non-irrigated	3.01	0.71	2.63	0.64
Willow	Irrigated	2.17	0.37	1.88	0.80
Willow	Non-irrigated	3.15	0.73	2.13	0.87

Table 3 Allometric relationship or linear regression coefficient between wood biomass and stem diameter measured at 8 cm in mm from ground. ($y=a*x$, a: slope, R^2 : coefficient of determination)

	February 2008	Linear regression $Woodmass=a*d8$		Power (non-linear regression) $Woodmass=a*d8^{(b')}$			Fresh weight approach	
		a=slope	R^2	a'=slope	b'=power	R^2	Fresh weight (ton.ha ⁻¹)	Moisture content %
Tree	Irrigation							
Eucalyptus	Irrigated	48.79	0.42	0.18	2.48	0.95	58.54	0.45
Eucalyptus	Non-irrigated	48.31	0.52	0.22	2.49	0.93	51.83	0.45
Poplar	Irrigated	13.24	0.64	0.06	2.59	0.93	42.38	0.47
Poplar	Non-irrigated	9.91	0.62	0.12	2.32	0.95	30.20	0.44
Willow	Irrigated	18.20	0.65	0.13	2.45	0.93	79.03	0.48
Willow	Non-irrigated	17.98	0.70	0.04	2.80	0.91	52.38	0.47

From these allometric relationships, leaf/wood biomasses were calculated and extrapolated to yield in oven dry ton by hectare, odt.ha^{-1} , and ANOVA was performed on the data obtained.

Volume of wood was calculated as the volume of a cylinder (Forestry Commission., 1975.). The volume was hence calculated as the basal area calculated with measurements of diameter at 8 cm from ground multiplied by the mean dominant length corresponding to tree species, irrigated or not. (Forestry Commission., 1975.)

3.2.2.2 Statistical analysis for wood biomass

The different wood biomass assessment approached yields are presented in Table 4 and the linear regression approach was preferred to the non-linear approach. Indeed, linear regression gave yields closer to the fresh weight approach than non-linear regression. For this reason, from this point, wood biomasses considered are the linear regressed.

Table 4 Comparisons of the final wood biomass obtained by different calculations methods in odt.ha^{-1} .

<i>Tree</i>	<i>Irrigation</i>	<i>Linear regression</i> <i>Woodmass=a*d8</i> <i>(ton.ha⁻¹)</i>	<i>Power regression</i> <i>Woodmass=a*d8^(b)</i> <i>(ton.ha⁻¹)</i>	<i>Fresh weight</i> <i>(ton.ha⁻¹)</i>
Eucalyptus	Non-irrigated	40.22±0.89	193.57±51.26	28.50±16.09
Eucalyptus	Irrigated	34.94±8.31	204.78±59.47	32.20±31.33
Poplar	Non-irrigated	17.34±2.71	22.95±10.10	16.91±6.15
Poplar	Irrigated	11.79±1.76	41.16±10.80	22.46±5.68
Willow	Non-irrigated	35.13±7.78	47.54±24.48	27.76±14.01
Willow	Irrigated	23.96±16.89	86.47±35.54	41.09±14.79

Therefore, the wood biomasses calculated with the linear regression and wood biomasses calculated from fresh weights were of the same range of values. But the wood biomasses calculated with the non-linear regression were between 1.4 and 7 times greater than the wood biomasses calculated from fresh weights. Therefore, the wood biomasses calculated from the linear regression were considered for statistical analysis. Biomass data had to be transformed to ensure residuals normal distribution.

Table 5 ANOVA table for log (biomass) from both irrigated and non-irrigated eucalyptus, poplar and willow (in bold, significant factors, $p < 0.05$)

	<i>Degree of - Freedom</i>	<i>Log(biomass) - F</i>	<i>Log(biomass) - p</i>
Intercept	1	20395.73	0.00
Date(Tree*Irrigation)	72	15.12	0.00
Tree	2	456.23	0.00
Irrigation	1	74.23	0.00
Tree*Irrigation	2	4.42	0.01
Error	153		
Total	230		

Irrigation increased wood biomass yield significantly. On average, wood biomass yield from irrigated trees was greater than wood biomass yield from non-irrigated trees. However, irrigation did not increase wood yield significantly for eucalyptus at any date. But irrigation did increase wood yield significantly for poplar trees from August 2006 until April 2007 and willow trees from January 2007 until May 2007.

For the whole period of experiment, poplar wood yields were always significantly lower than eucalyptus and willows' wood yield for both irrigated and non-irrigated plots. During the first growing season, from July 2006 until May 2007, non-irrigated willow trees were presenting significantly lower yield than eucalyptus trees. However, there was no significant difference between irrigated willow trees and eucalyptus trees. Hence, willow trees responded the most to irrigation in terms of wood biomass.

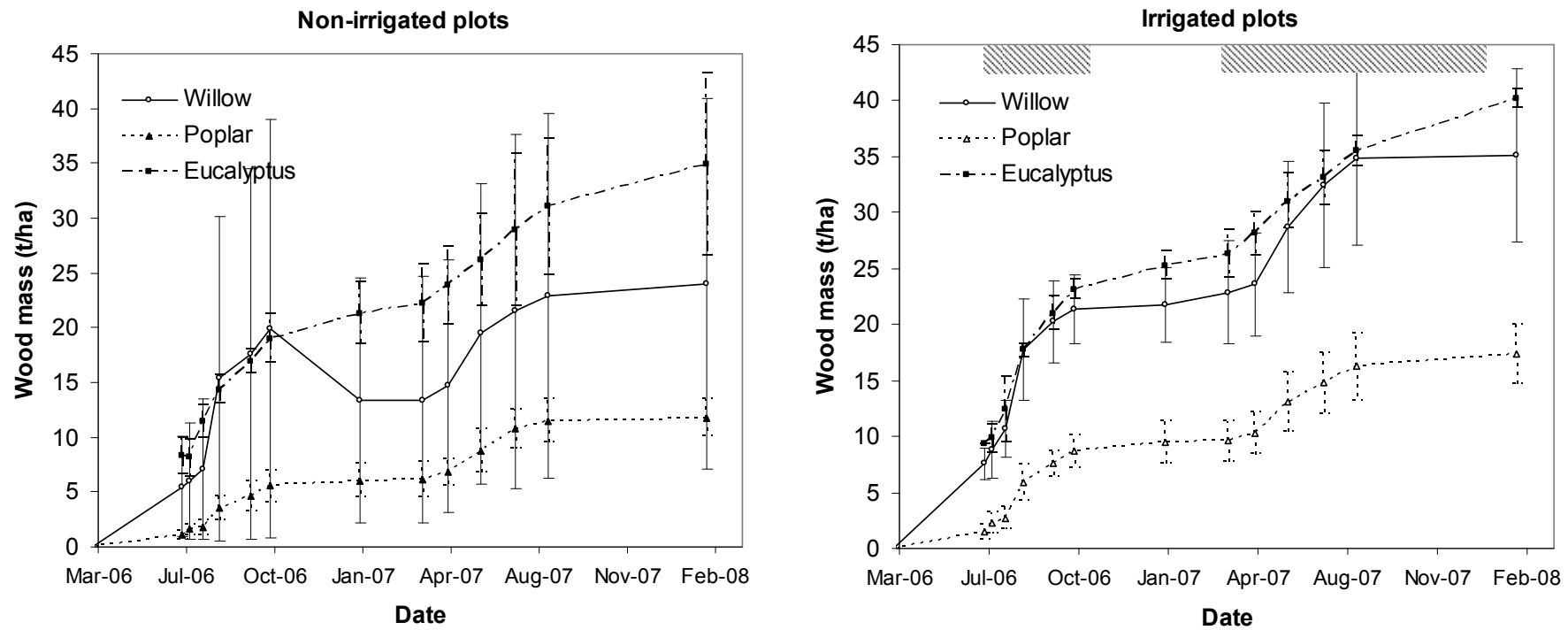


Figure 5 Evolution of wood biomass ($\text{odt} \cdot \text{ha}^{-1}$) from July 2006 until February 2008. (Dashed zones represents the periods when irrigation was on). Month 0 was March 2006. Vertical bars denote standard deviations.

Wood yield in odt.ha^{-1} , considered as stem biomass, had the same patterns for irrigated and non-irrigated trees. This was in accordance with stem length growth rates; willow yields and also growth rates were greater than poplar and eucalyptus ones. For all trees, irrigated or not, during the second growing period, growth rates were lower than during the first growing period.

Because of the cluster planting, in February 2008, the field can be compared to an SRC crop of 3 years old for above ground material and harvested biomass in February 2008 can be considered as a first harvest. Commercial site reported yields after the first harvest are typically between 5 to 9 $\text{odt.ha}^{-1}.\text{yr}^{-1}$ (Defra, 2002.). For willows, irrigated plots yield was $11.7 \pm 2.6 \text{ odt.ha}^{-1}.\text{yr}^{-1}$ and $8.0 \pm 5.6 \text{ odt.ha}^{-1}.\text{yr}^{-1}$ for non irrigated plots. And for poplar, $5.8 \pm 0.9 \text{ odt.ha}^{-1}.\text{yr}^{-1}$ for irrigated plots and $3.9 \pm 0.6 \text{ odt.ha}^{-1}.\text{yr}^{-1}$ for non-irrigated plots. Hence, yields obtained in Cranfield were average for willows and low for poplars as the planting density of 13,060 trees/ha was comparable to the 12,000 trees. ha^{-1} of the commercial sites (Defra, 2002.). For eucalyptus, reported yields ranged between 12 and 22 odt.ha^{-1} after 3 years with a plantation density of 4000 trees ha^{-1} (Sochacki et al., 2007). Hence, yields of $13.5 \pm 0.3 \text{ odt.ha}^{-1}.\text{yr}^{-1}$ and $11.7 \pm 2.8 \text{ odt.ha}^{-1}.\text{yr}^{-1}$ for non irrigated plots are high compared to yields in the literature. As there was a significant positive effect of irrigation during the whole experiment for eucalyptus yields, these high yields could reflect a greater adaptation of eucalyptus to a WaterRenew system than poplar and willows, even though eucalyptus was a non-endemic species to the climato-edaphic conditions of Cranfield. This will be verified by water use calculations.

Table 6 Mean length (L), mean dominant height (MDH), basal area (BA), volume ($V = L \cdot BA$), leaf area index (LAI), calculated dry foliage mass (M_f) oven dry wood mass (M_w) and wood density after two seasons of irrigation. Treatment regimes are irrigated and non-irrigated (mean ± 0.95 confidence interval).

Tree	Irrigation	L (m)	MDH (m)	BA ($\text{m}^2.\text{ha}^{-1}$)	V ($\text{m}^3.\text{ha}^{-1}$)	Max LAI	M_f (odt.ha^{-1})	M_w (odt.ha^{-1})	Density (odt.m^{-3})
Eucalyptus	Non-irrigated	5.4 ± 0.6	5.4	10.5 ± 0.6	56.6	1.7	12.7 ± 1.4	40.2 ± 0.9	0.618
Eucalyptus	Irrigated	4.8 ± 0.6	10.5	13.8 ± 0.9	66.2	3.6	12.72 ± 1.5	34.9 ± 8.3	0.607
Poplar	Non-irrigated	2.8 ± 0.2	3.5	6.6 ± 0.8	18.6	4.4	3.5 ± 0.9	17.3 ± 2.7	0.635
Poplar	Irrigated	3.6 ± 0.2	6.6	8.4 ± 0.6	30.2	4.3	3.3 ± 0.9	11.8 ± 1.8	0.573
Willow	Non-irrigated	5 ± 0.3	5.9	9.5 ± 0.9	47.6	2.7	4.4 ± 1.9	35.1 ± 7.8	0.503
Willow	Irrigated	5.4 ± 0.3	9.5	12.9 ± 0.7	69.4	3	4.2 ± 0.7	24.0 ± 16.9	0.506

Wood density is an essential parameter characterising wood properties as it affects directly fibrous and solid wood products (Pliura et al., 2007). Usually, higher wood densities are advantageous for both pulping and burning (Miranda et al., 2001).

At harvesting in February 2008, densities were calculated as the ratio of wood mass produced (M_w in odt.ha^{-1}) and volume of green stem (calculated as a cylinder of base, the diameter measured at 8 cm from ground (Forestry Commission., 1975.)). Moreover, wood density serves in the calculation of the FVI (fuel value index, kJ.m^{-3}) and FVI is directly proportional to it.

First, on observing wood densities of all the species under different treatments, irrigated eucalyptus and poplar trees presented slightly lower wood density than non-irrigated trees (11% less for poplar and 2% less for eucalyptus trees). However, irrigated willow' wood densities are 1 % higher than non-irrigated willow' ones (Table 5). As densities are reported not to be highly correlated to growth rate (Dutilleul et al., 1998); the analysis of nutrient concentrations might explain these differences.

Let's consider the different wood densities observed and especially if there is any significant effect of irrigation on wood density.

According to Miranda et al (2001), 3 year old *E. globulus* trees are reported to have density between $430\text{--}486 \text{ kg.m}^{-3}$, i.e. densities of *E.gunnii* in Cranfield represent sensible values even though higher (618 kg.m^{-3} for non-irrigated eucalyptus and 607 kg.m^{-3} for irrigated ones, Table 5). For willow, Klasnja (Klasnja et al., 2002) reported willow wood density in SRC after 2 years around 410 kg.m^{-3} for non- fertilised. For Cranfield, calculated willow densities are higher (503 kg.m^{-3} for non-irrigated trees and 506 kg.m^{-3} for irrigated trees, Table 5). The higher densities might be explained by the uncertainties around volume calculations as densities for both irrigated and non-irrigated trees, are higher than average. But as no volume measurements were conducted during harvest, it cannot be verified. For poplar, Pilura (Pliura et al., 2007) reported densities for different clones of poplar range from 230 kg.m^{-3} to 519 kg.m^{-3} . Hence, Cranfield poplar wood densities are average (635 kg.m^{-3} for non-irrigated trees and 573 kg.m^{-3} for irrigated trees, Table 5) and in the range reported in the literature. Hence, the same story is observed for poplar wood densities than for willow and wood nutrients content might provide an explanation.

3.2.2.3 Statistical analysis of cumulative foliar biomass

As foliar biomass was calculated by linear regression of diameter measurements, the foliar biomasses calculated are cumulative foliar biomasses.

Cumulative foliar biomass data had to be transformed to ensure residuals normal distribution.

Table 7 ANOVA table for log (biomass) from both irrigated and non-irrigated eucalyptus, poplar and willow (in bold, significant factors, $p < 0.05$)

	<i>Degree of - Freedom</i>	<i>Log(biomass) - F</i>	<i>Log(biomass) - p</i>
Intercept	1	986.87	0.00
Date(Tree*Irrigation)	68	20.11	0.00
Tree	2	69.34	0.00
Irrigation	1	0.15	0.70
Tree*Irrigation	2	6.21	0.00
Error	145		
Total	218		

Irrigation did not have a significant effect on foliar mass growth. On average, even though not significantly, non-irrigated trees produced 5 % more foliar mass than irrigated trees for willow and poplar ($3.50 \pm 0.9 \text{ odt.ha}^{-1}$ for non-irrigated against $3.35 \pm 0.9 \text{ odt.ha}^{-1}$ for irrigated for poplar, and $4.37 \pm 1.9 \text{ odt.ha}^{-1}$ for non-irrigated against $4.18 \pm 0.8 \text{ odt.ha}^{-1}$ for irrigated for willow). For eucalyptus, non-irrigated plot yields were 1 % greater than non-irrigated ones ($12.72 \pm 1.54 \text{ odt.ha}^{-1}$ and $12.70 \pm 1.36 \text{ odt.ha}^{-1}$).

There was a significant tree species effect with poplar ($3.50 \pm 0.9 \text{ odt.ha}^{-1}$ for non-irrigated against $3.35 \pm 0.9 \text{ odt.ha}^{-1}$ for irrigated) producing significantly less foliar biomass than eucalyptus ($12.72 \pm 1.54 \text{ odt.ha}^{-1}$ for irrigated and $12.70 \pm 1.36 \text{ odt.ha}^{-1}$ for non-irrigated) and willow ($4.37 \pm 1.9 \text{ odt.ha}^{-1}$ for non-irrigated against $4.18 \pm 0.8 \text{ odt.ha}^{-1}$ for irrigated) for both irrigated and non-irrigated trees (Table 5). Eucalyptus foliar yields were significantly higher than willow only when irrigated. Hence irrigation boosted eucalyptus foliar yield more than willow foliar yield.

Eucalyptus consistently produced more foliar biomass than willow but it was significant only when non-irrigated (+2.9 times). Eucalyptus and willow produced significantly higher foliar biomass than poplar for both irrigated and non-irrigated trees (3.6 times more for non-irrigated trees, 3.8 times more for irrigated trees for eucalyptus and poplar, and 1.25 times more for both non-irrigated and irrigated trees for willow and poplar). Irrigation decreased cumulative foliar biomass yield (odt.ha^{-1}) but not

significantly and the average dry mass of leaf produced on irrigated plots was lower than the average produced on non-irrigated plots for the 3 tree species. The negative effect of effluent irrigation on foliar yield was significant for the 3 tree species and for almost all the duration of the experiment. The last 2 measurements in July 2007 and August 2007 did not show significant effect of irrigation. Here as well, the error bars were very different from one species to the other and through time, they enlarge and reflect the greater variability of stem diameters. In particular, willow trees' larger error bars reflect the high variability of stem diameters, on which yield assessment was performed using the allometric relationship considered.

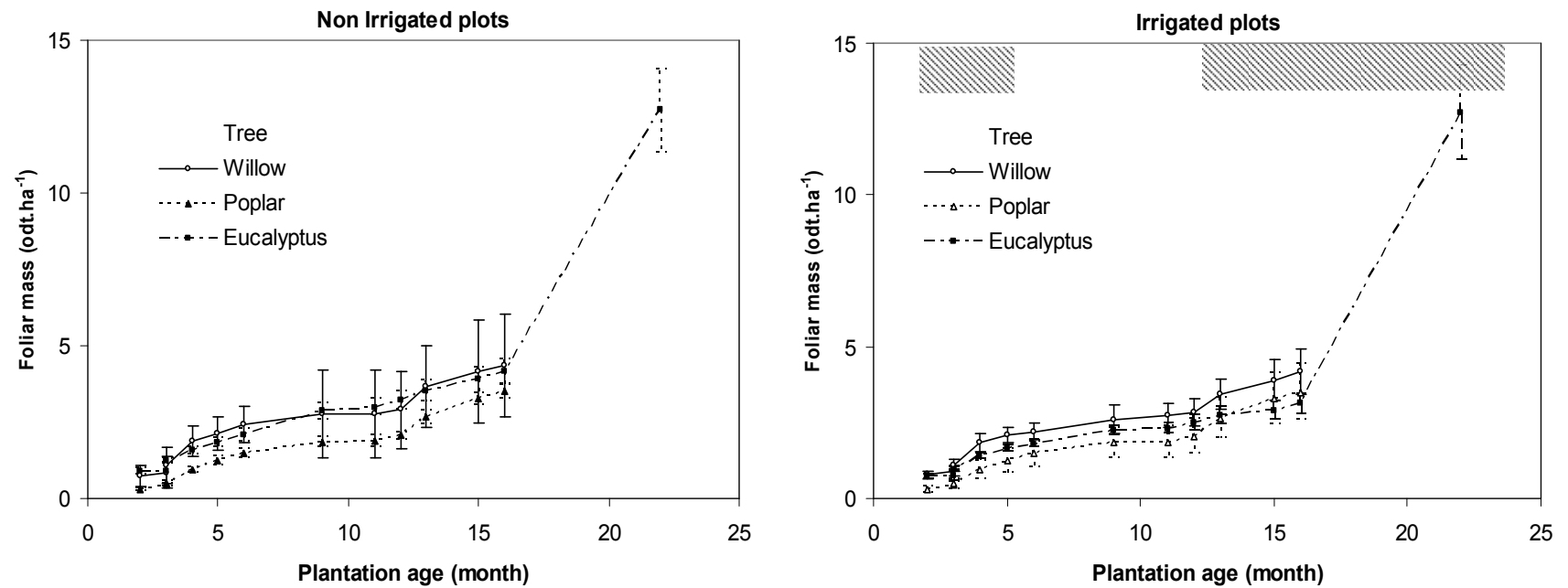


Figure 6 Evolution of cumulative foliar biomass (odt.ha⁻¹) from July 2006 until February 2008. (Dashed zones represents the periods when irrigation was on. Month 0 was March 2006 and month 22, February 2008. Vertical bars denote standard deviations).

The patterns for cumulative foliar biomass evolution were the same for all trees, irrigated or not. Willow presented the highest foliar yield for the whole duration of the experiment, for both irrigated and non-irrigated plots. But for non-irrigated plots, eucalyptus and poplar cumulative foliar biomass grew at very same rates until January 2007 (month 9) whereas for irrigated plots, poplar trees were already overtaking eucalyptus trees from July 2006 (month 3). From January 2007 until May 2007 (month 13); i.e. with poplar losing their leaves from October until February, for non-irrigated plots, eucalyptus cumulative foliar biomass was significantly greater than poplar cumulative foliar biomass. However once the growing season started, poplar cumulative foliar biomass overtook again eucalyptus cumulative foliar biomass. .

3.2.3 Leaf Area Index

LAI data had to be transformed to ensure residuals normal distribution.

Table 8 ANOVA table for log (LAI) from both upstream and downstream sampling (in bold, significant factors, $p < 0.05$)

	<i>Degree of - Freedom</i>	<i>Log(LAI) - F</i>	<i>Log(LAI) - p</i>
Intercept	1	155.90	0.00
Date(Tree*Irrigation)	3	406.79	0.00
Tree	1	10.02	0.00
Irrigation	78	7.00	0.00
Tree*Irrigation	3	0.21	0.89
Error	163		
Total	248		

Irrigation increased LAI significantly and LAI for irrigated plots were greater than under non-irrigated plots. There was also a significant species effect; willow and poplar plots were presenting significantly higher LAI than eucalyptus plots. Irrigation increased LAI significantly only in April 2007 for willow, in August 2006 for poplar and in August 2006 and September 2007 for eucalyptus.

In summer 2007, for the purposes of another experiment and because of the very wet conditions, automated irrigation was turned off for one week in July 2007. But this very week was very hot and dry week. Consequently, trees were suddenly very stressed and willow and poplar trees partly lost their leaves as a defence mechanism against drought. This episode corresponds to the sudden unexpected decrease of LAI during summer 2007 (month 15) in Figure 8.

LAI evolution reflects tree leaf development and the two growing seasons are clearly identifiable from month 4 (July 2006) to month 8 (October 2006) and from month 12 (April 2007) to month 18 (November 2007 even if not measured, leaves had fallen by that date).

In section 3.2.2.3, irrigation did not have a significant effect on cumulative foliar biomass and had rather a negative effect with irrigated trees producing less leaves than non-irrigated trees. But in this section, irrigation is reported to have a significant positive effect on LAI. This looks contradictory as LAI definition by FAO guidelines (Allen, 1998.) is “the leaf area in m^2 (upper side only) per unit area of soil m^2 below it.” Therefore, if LAI increases significantly, it means the upper sunlit portion of leaf area should have also increased. Consequently, to some extent foliar biomass should have increased as well, which is not the case in our experiment. Sunscan (Delta T) calculates LAI by measuring both solar radiation reaching the ground under the trees in a plot and direct solar radiation at the same location. As irrigation increased wood biomass (section 3.2.2.2) significantly, even though foliar biomass did not increase significantly, the wood biomass would have prevented radiation to reach the ground and increase LAI values.

For the first growing season, willow LAI were greater than poplars’, themselves greater than eucalyptus but for the second growing season, and for both irrigated and non-irrigated plots, poplars’ LAI were significantly greater than willows’, they were in turn greater than eucalyptus’.

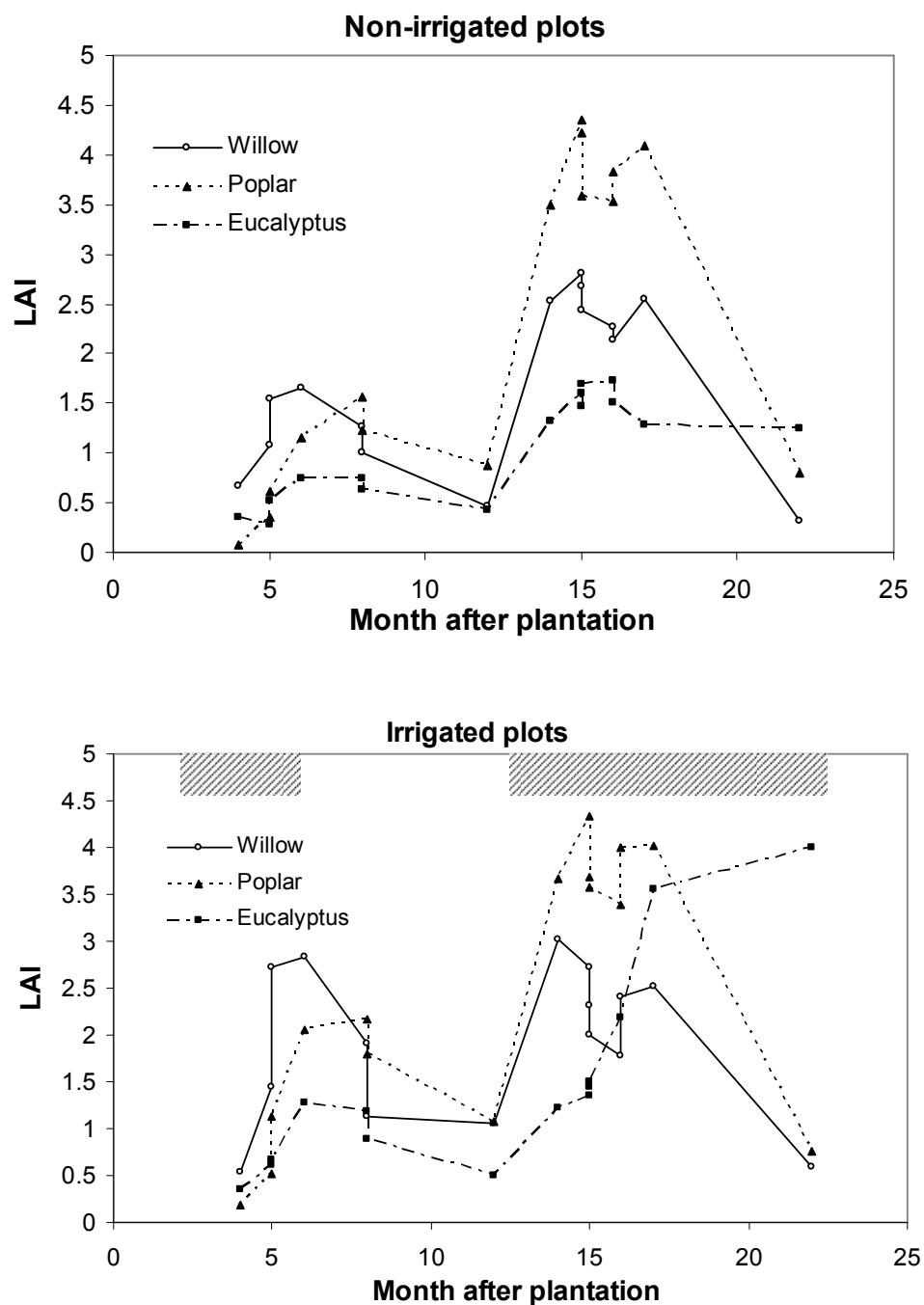


Figure 7 Evolution of LAI from July 2006 until February 2008. (Dashed zones represents the periods when irrigation was on. Month 0 was March 2006.)

3.3 WATER USE

3.3.1 Irrigated volumes per trees

The same volume of secondary treated effluent was applied by type of cover even if there might be differences in water content among replicates. The volumes were calculated from the number of times the pump was turned on within an hour. Once turned on, the pump delivered 87 mL.m^{-2} per minute (Figure 4). From July 2006 until January 2007, the maximum irrigation capacity was of 15.7 mm.day^{-1} . This irrigation maximum capacity was doubled to 31.4 mm.day^{-1} from August 2007 to January 2008 by installing more drippers.

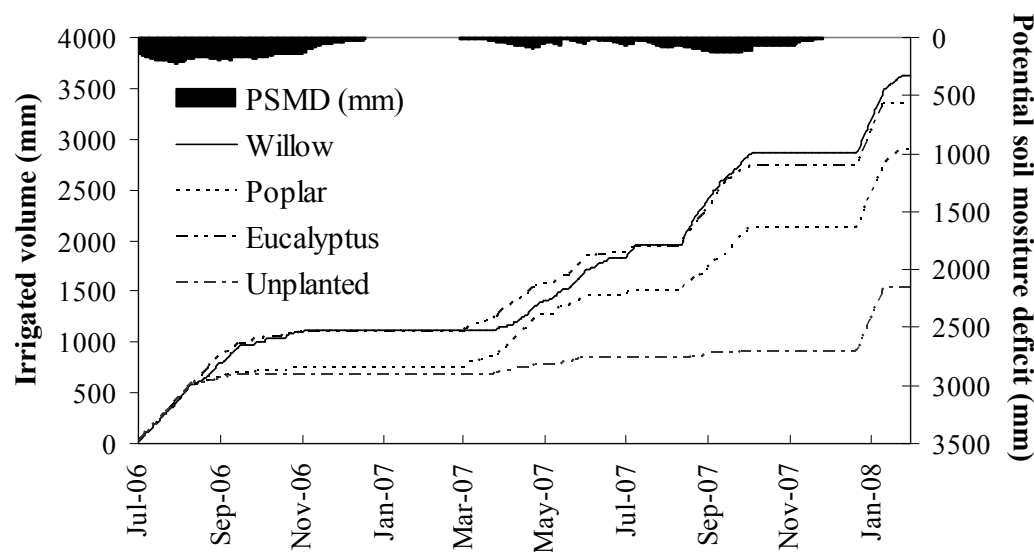


Figure 8 Irrigated volume on *E.gunnii*, *P. Trichocarpa*, *S.viminalis* and unplanted plots and PSMD from July 2006 until January 2008.

Figure 8 illustrates effluent delivery evolution on plots with different covers. First of all, there is a good graphical correlation between PSMD evolution and applied effluent volumes.

From July 2006 to September 2006, the effluent delivery rate is the same under all covers. During this period, irrigation system settings allowed the soil profile to be recharged to the field capacity value that the irrigation system was set for. From September 2006, a differentiation in effluent application rate with covers became apparent; willow and eucalyptus took up more water so that they received more effluent at a comparable rate to that of the previous period. However there was a net slow down in effluent delivery for poplar and unplanted plots, and this lasted until

March 2007. From March 2007 or the beginning of the second growth period, irrigation rates were different for each tree species. Poplar took up soil water at the fastest rate inducing a faster rate of irrigation until June 2007. Eucalypts water use was lower and willow's even less. When a drier period started again from mid August 2007 until October 2007, trees uptake and therefore effluent irrigation rate increased again with greater rate than at the beginning of the growth period in March 2007.

Then, in order to push the system, a manual irrigation, independent of moisture in soil, was set during January 2008. Effluent was delivered until excessive ponding forced a cessation of irrigation first on eucalyptus planted plots and then on unplanted plots. Because harvest was programmed for the second week of February 2008, irrigation on poplar and willow plots was stopped at the beginning of February 2008. At the end of the experiment, 3,625 mm of irrigation was applied on willow plots, 2,895 mm on poplar plots, 3,345 mm on eucalyptus plots and 1,536 mm on unplanted plots.

As trees were planted in March, as cuttings of 20 cm, for willow and poplar, or 50 cm pre-potted trees eucalypts, in July, it was only the beginning of the growing season, and transpiration was considered as still limited; $LAI < 0.6$ for the 3 species (Figure 8, section 3.2.3 page 4-35). As irrigated volumes were recorded, when irrigated volumes started to differentiate under the different covers, the preliminary soil profile wetting up to field capacity and hydrological equilibrium could be considered as reached.

From July 2006 until September 2006, the system was delivering effluent at a maximum rate on all cover (Figure 8). This step can be seen as the wetting up of soil profile to field capacity. From September 2006, cover started to induce a differentiation on volume of effluent irrigated, on one hand *E.gunnii* and *S.viminalis* kept receiving the maximum amount deliverable from the system until October while *P.trichocarpa* and unplanted plots received 30% less (Table 8). At the end of 2006, this resulted to an application of 52 % of effluent on Poplar and Unplanted plots (749 mm and 678 mm respectively) on one hand compared to willow and eucalyptus (1,115 mm and 1,103 mm respectively) on the other hand.

From 2007, irrigation rates on poplar planted plots got closer to willow and eucalyptus ones than unplanted plots. At the end of 2007, the volume applied on poplar plots represented more than 80% of the volume of effluent applied on willow and eucalyptus (1,379 mm, 1,752 mm and 1,635 mm respectively) against less than 14 % for unplanted plots (222 mm).

Table 9 Volume of effluent irrigated (mm), nitrogen, N, and phosphorus, P applied in kg.ha⁻¹.

	2006				2007			
	<i>Willow</i>	<i>Poplar</i>	<i>Eucalyptus</i>	<i>Unplanted</i>	<i>Willow</i>	<i>Poplar</i>	<i>Eucalyptus</i>	<i>Unplanted</i>
Volume irrigated (mm)	1115	749	1103	678	1752	1379	1635	222
N applied (kg.ha ⁻¹)	331	223	328	201	520	409	486	66
P applied (kg.ha ⁻¹)	33	22	33	20	53	41	49	7
K applied (kg.ha ⁻¹)	223	150	221	136	350	276	327	44
Na applied (kg.ha ⁻¹)	451	308	424	268	1508	1242	1187	506

Irrigated plots for all covers, presented greater water use than non-irrigated plots with the same cover for the same year (Table 8); for eucalypts and willow, more than 3 times, for poplar more than twice and for unplanted plots, twice in 2006 (relatively dry year, Figure 3) but only 10 % more in 2007 (relatively wet year, Figure 3).

Water balance was calculated for all the plots regrouped by replicates.

During the first year of irrigation, willow and eucalyptus plots received over 250 kg-N.ha⁻¹, DEFRA's limitation for N annual application (MAFF 2000), more than 30 kg-P.ha⁻¹ and between 150-220 kg-K.ha⁻¹. DEFRA fertiliser recommendations for hops were considered for comparison in RB 209 (MAFF 2000). For soil presenting P index of 2 as Cranfield site clay, RB 209 recommends to apply 125 kg-P.ha⁻¹ and for soil presenting K index 2 as Cranfield site clay, it recommends applying 200 kg-K.ha⁻¹. Thus, N application was high in Cranfield compared to RB 209, low (<1/4) for P and in accordance for K.

During the second year of irrigation, all 3 tree species received over 400 kg-N.ha⁻¹, 40 kg-P.ha⁻¹ and over 280 kg-K.ha⁻¹. RB 209 recommends 200 kg-N.ha⁻¹ for clay soils from the second year and subsequent years after establishment, for soil presenting index 2 for P and K, RB 209 recommends an application of 150 kg-P.ha⁻¹ and 270 kg-K.ha⁻¹. Thus, N application was double in Cranfield compared to RB 209, low (<1/3) for P and in accordance for K.

3.3.2 Water use efficiency

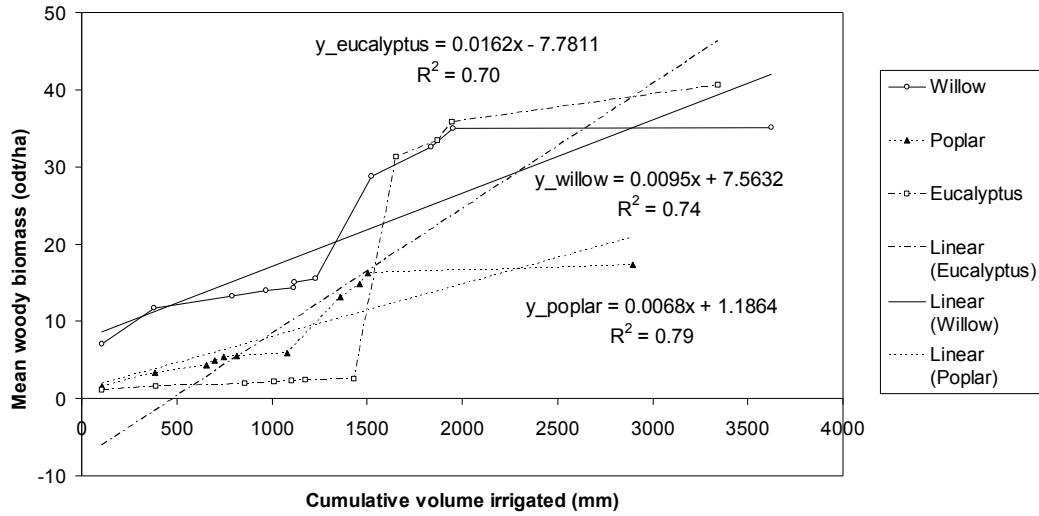


Figure 9 Effluent use efficiency for woody biomass production and corresponding linear regression on averaged data for willow, poplar and eucalyptus from July 2006 until January 2008.

Water use efficiencies to produce woody biomass were compared for each tree species in Figure 9. For a WaterRenew system, the best performing species in terms of water use is the one using the largest amount of effluent to produce the greatest amount of biomass, i.e. species with low water use efficiency. Hence, for the species studied at Cranfield, eucalyptus was the best performing as it presented the steepest slope meaning the greatest amount of effluent was required to produce the same amount of woody biomass (slope_eucalyptus= 0.0162 compared to slope_willow= 0.0095 and slope_poplar= 0.0068). However, for the endemic species, the optimised amounts to apply to produce a given quantity of woody biomass were exceeded during the experiment. Indeed, trees' water use efficiency curves presented a saturation shape from 1,503 mm of effluent applied for poplar and 1953 mm for willow. For eucalyptus, this limit was not reached during the short time of experiment.

Jorgensen defined WUE as follow (van Wijk et al., 2003):

$$WUE = \frac{\text{above ground crop}(g)}{\text{Transpiration}(kg)}$$

– above ground crop : leaf + wood **Equation 14**
 – Transpiration = $\Delta \text{Irrigation}_{\text{Tree-Unplanted}}$

Therefore, with this definition, WUE represents the amount of water needed to be transpired to produce one gram of above ground biomass for irrigated trees.

Table 10 WUE (g dry biomass per kg of water transpired) on irrigated willow, poplar and eucalyptus with cumulative data at the end of the experiment in February 2008.

Tree	Total above ground dry mass (odt.ha ⁻¹)=100*g.m ⁻²	Total transpiration (mm)=kg.m ⁻²	WUE (g/kg)
Willow	27.3	1967	1.39
Poplar	13.2	1228	1.08
Eucalyptus	53.3	1838	2.90

Lindroth A. and Cienciala E., (1996) reported that for *S.viminalis*, the published range for WUE was 2.9 to 5.9 g.kg⁻¹. Hence, a WUE of 1.39 g.kg⁻¹ calculated for willow is low. This is confirmed in another study. (Martin and Stephens, 2006/2) also reported on a trial in Silsoe, 15 miles south-west, where they grow willow in lysimeter filled with clay soil, a WUE of 1.74 for the second year. For Eucalyptus, (Li, 2000) reported a WUE ranging from “1.64–2.36 g dry matter accumulation per kg water transpired” for eucalyptus (not *E.gunnii* but *E. microtheca* seedlings) and Le Roux (Le Roux et al., 1996) reported for 6 clones of *E.grandis*, a WUE for the above ground crop ranging 1.15 to 1.99 g.kg⁻¹. Therefore Cranfield’s calculated value of 2.90 g.kg⁻¹ is quite high. Nutrient use efficiencies might explain this high value.

For poplar, Liang et al. (2006) studied *Populus simonii* and WUE with changing field capacity. For a field capacity of 55 %, Liang reported a WUE of 3.45 to 5.26 g.kg⁻¹ depending on the development stage. Again, Cranfield WUE for poplar is lower (1.08 g.kg⁻¹) than for other trees. These differences might be explained by the fact Cranfield grew a different clone, *P.trichocarpa*, and the study of nutrient use efficiency might explain this lack of efficiency or reflect a greater amount of stress on these trees.

3.3.3 Crop factors

Transpiration data calculated in the previous paragraph was used to calculate K_c with Equation 8 where ET_c is overestimated as soil evaporation is approximated using ET_0 .

$$K_c = \min\left(\frac{Tr + ET_0}{ET_0}, 2.5\right) \quad \text{Equation 8}$$

Then, calculated values were modelled to establish the relationship between time of year and expected K_c for each species.

The equations used to model K_c are presented in Table 10.

Table 11 K_c models for willow, poplar and eucalyptus.

$x=DoY-195$	K_{c_willow}
$0 < x < 185$	$y = -2.88 \cdot 10^{-4} \cdot x^2 + 0.052 \cdot x + 0.2$
$185 < x < 282$	$y = 0$
$282 < x < 276$	$y = 5 \cdot 10^{-3} \cdot (x - 282)$
$276 < x < 447$	$y = 2.5$
$447 < x < 500$	$y = -16.3 \cdot 10^{-3} \cdot (x - 447) + 2.5$
$500 < x < 600$	$y = 0$
$x=DoY-195$	K_{c_poplar}
$0 < x < 183$	$y = -2.83 \cdot 10^{-4} \cdot x^2 + 0.052 \cdot x + 0.2$
$183 < x < 283$	$y = 0$
$283 < x < 271$	$y = 5 \cdot 10^{-3} \cdot (x - 283)$
$271 < x < 406$	$y = 2.5$
$406 < x < 494$	$y = -0.028 \cdot (x - 406) + 2.5$
$494 < x < 600$	$y = 0$
$x=DoY-195$	$K_{c_eucalyptus}$
$0 < x < 182$	$y = -2.31 \cdot 10^{-4} \cdot x^2 + 0.046 \cdot x + 0.2$
$182 < x < 227$	$y = 1$
$227 < x < 264$	$y = 0.03 \cdot (x - 227)$
$265 < x < 410$	$y = 2.5$
$410 < x < 488$	$y = -0.03 \cdot (x - 410) + 2.5$
$488 < x < 600$	$y = 1$

Both calculated and modelled K_c were represented in Figure 10 for willow, Figure 11 for poplar and Figure 12 for eucalyptus.

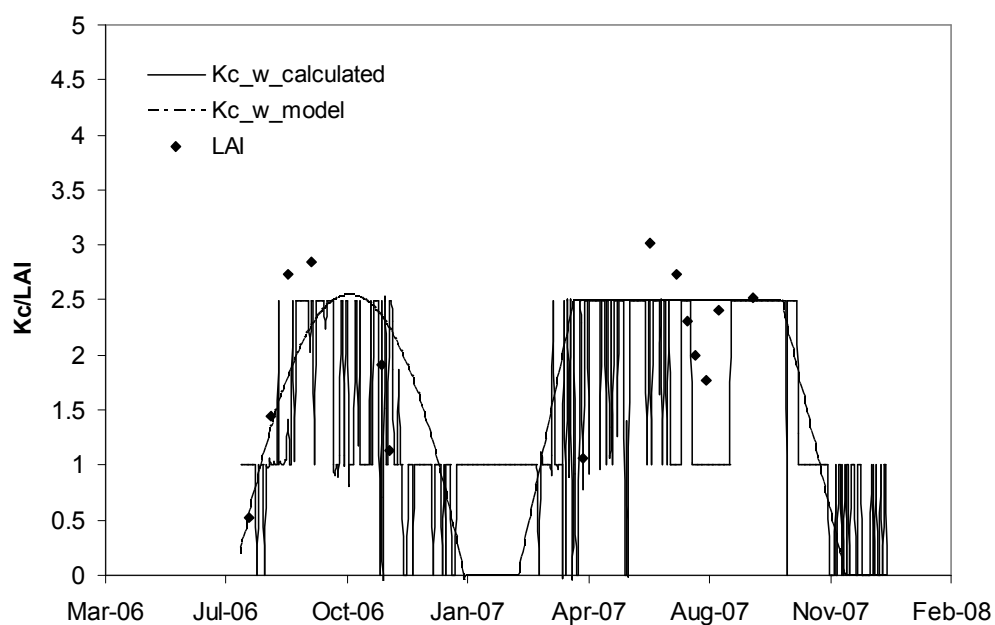


Figure 10 Evolution of K_c for irrigated willow trees, calculated and modelled (---) and LAI.

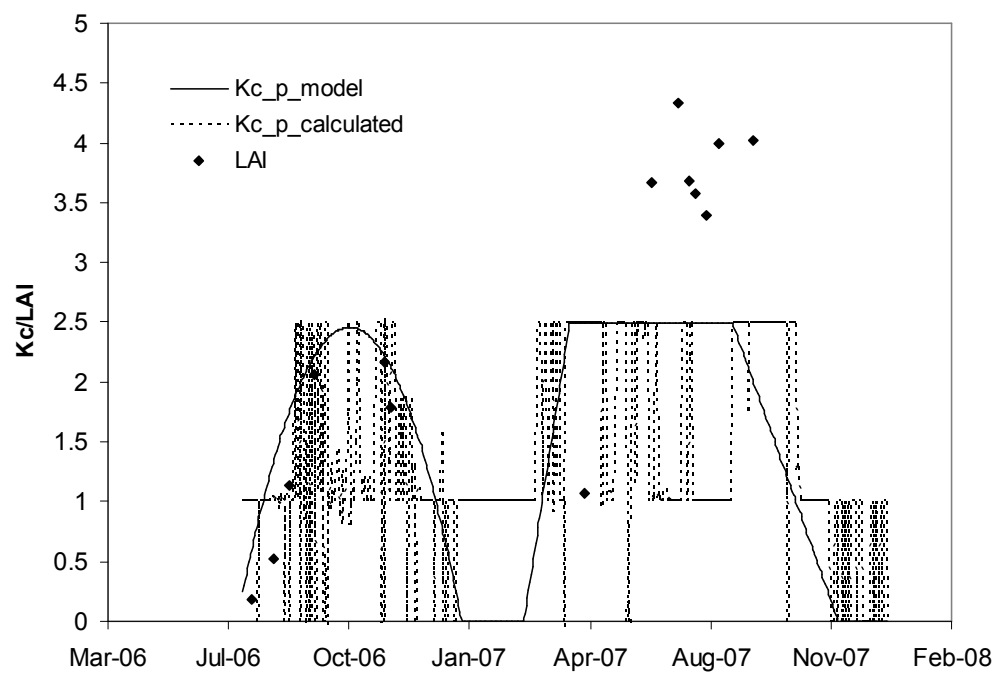


Figure 11 Evolution of K_c for irrigated poplar trees, calculated and modelled (---) and LAI.

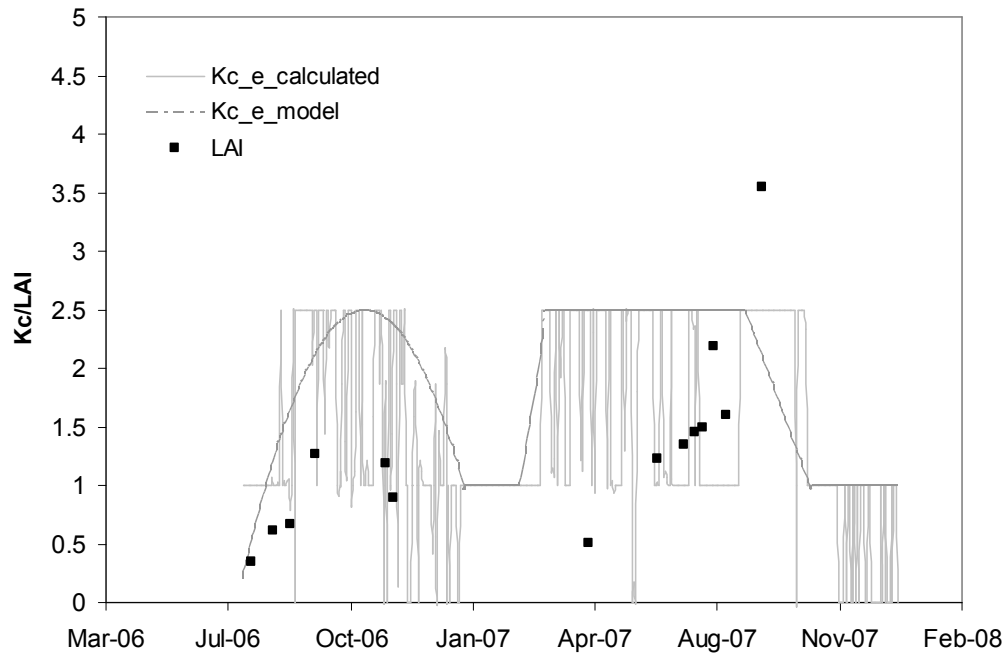


Figure 12 Evolution of K_c for eucalyptus trees, calculated and modelled (---) and LAI. As eucalyptus trees do not lose their leaves during winter, it was considered E_{t0} would not be lower than grass, hence E_{t0} , therefore K_c was equalled to 1.

K_c evolution in time is the same for all trees; the quick increase from the beginning of spring (March) reflects leaf growth and establishment, then a stabilisation around $K_c=2.5$ until the beginning of autumn (mid-September) corresponding to leaf yellowing and finally, leaf fall with $K_c \approx 0$ for mid-November. There is an exception for eucalyptus as it does not lose its leaves during the winter and eucalyptus trees can potentially keep transpiring at the rate of grass; i.e. with a $K_c=1$ and not $K_c=0$.

K_c even though not directly proportional to LAI, depends on LAI value as LAI reflects canopy development, hence leaf mass. Allen (1998) relates K_c to LAI (Allen, 1998.).

However it is not a linear equation:

$$(K_{c_{\text{basal_mid}}} = K_{c_{\text{min}}} + (K_{c_{\text{basal_full}}} - K_{c_{\text{min}}})(1 - \exp[-0.7 * \text{LAI}]))$$

Therefore, K_c (calculated and modelled) was plotted with LAI for a graphical assessment (Figure 10, 11, 12) and a visual correspondence could be observed.

On comparing K_c calculated from Cranfield data and from the literature (Table 11), Cranfield K_c were higher but it was expected because Cranfield plots are small and the edge effect very important. K_c values are important because they are directly related to evapotranspiration rates (Equation 5) and evapotranspiration rates define directly the amounts of effluent irrigable on the field. Therefore, a tree species with higher K_c year long will transpire more and therefore uptake more water and it will be possible to irrigate more effluent to it.

Table 12 K_c reported in the literature for eucalyptus, poplar and willow.

	<i>Crop coefficient (K_c)</i>		
	Initial growth	Intermediate growth	End of growth
Eucalyptus	0.50 ^a	1.20 ^a	0.50 ^a
Poplar	0.30 ^a	1.00 ^a	0.30 ^a
Willow	-	1.10-1.50 ^b	-

^a from (Myers et al., 1999) ^b from (Jørgensen and Endorichio, 2001)

3.4 AVERAGE ANNUAL REMOVAL OF NUTRIENTS AND NUTRIENT USE EFFICIENCY

3.4.1 Nutrient concentration in leaf and wood

3.4.1.1 Leaf biomass composition

N, P K (in % of foliar biomass) data did not need to be transformed to ensure residuals normal distribution.

The results are presenting in ANOVA tables (Table 12 for leaf).

Table 13 ANOVA table for N, P, K, C (%) in leaf material from both irrigated and non-irrigated willow, poplar, eucalyptus (in bold, significant factors, $p < 0.05$)

	<i>Degree. of Freedom</i>	<i>P__% - F-</i>	<i>P__% - p-</i>	<i>K__% - F-</i>	<i>K__% - p-</i>
Intercept	1	7677.8	0.00	6993.84	0.00
Date(Tree*Irrigation)	18	10.08	0.00	25.67	0.00
Tree	2	163.37	0.00	38.29	0.00
Irrigation	1	50.99	0.00	0.57	0.45
Tree*Irrigation	2	1.01	0.37	15.89	0.00
Error	134				
Total	157				
	<i>Degree. of Freedom</i>	<i>N__% - F-</i>	<i>N__% - p-</i>	<i>C__% - F-</i>	<i>C__% - p-</i>
Intercept	1	10508.33	0.00	313034.4	0.00
Date(Tree*Irrigation)	18	13.61	0.00	4.3	0.00
Tree	2	146.63	0.00	45.6	0.00
Irrigation	1	22.63	0.00	24.2	0.00
Tree*Irrigation	2	1.70	0.19	0.1	0.89
Error	134				
Total	157				

Nutrients content in leaf was significantly affected by the tree's stage of development for all trees (Table 12, $p > 0.05$ for N, P, K and C). P and N were getting more concentrated from July to October. Whereas for K, which concentration would decrease from August to October. And C concentration will rise from October to the summer and decrease again towards the autumn.

Concentrations of nutrients were significantly dependent on tree species (Table 12, $p < 0.05$ for N, P, K and C). The order of concentrations was the same for all nutrients for irrigated and non-irrigated trees and the same order for P, $N_{\%willow} > P, N_{\%poplar} > P, N_{\%eucalyptus}$ (Table 13). K concentrations in leaf were classified as follow; $K_{\%poplar} > K_{\%willow} > K_{\%eucalyptus}$. And C concentrations in leaf were classified as follow $C_{\%eucalyptus} > C_{\%poplar} > C_{\%willow}$.

Irrigation also consistently increased N and P concentrations in leaf for the tree species, therefore, the more N and P, the more it was concentrated in the leaves.

Table 14 P, K, N, C concentrations (%) in eucalyptus, poplar and willow non-irrigated and irrigated.

<i>Tree</i>	<i>Irrigation</i>	<i>P_% Mean</i>	<i>P_% Std.Err.</i>	<i>K_% Mean</i>	<i>K_% Std.Err.</i>
Eucalyptus	Non-irrigated	0.11	0.00	1.11	0.09
Poplar	Non-irrigated	0.17	0.01	1.51	0.05
Willow	Non-irrigated	0.18	0.00	1.14	0.02
Eucalyptus	Irrigated	0.13	0.01	1.06	0.10
Poplar	Irrigated	0.19	0.01	1.37	0.07
Willow	Irrigated	0.22	0.01	1.34	0.08
<i>Tree</i>	<i>Irrigation</i>	<i>N_% Mean</i>	<i>N_% Std.Err.</i>	<i>C_% Mean</i>	<i>C_% Std.Err.</i>
Eucalyptus	Non-irrigated	1.68	0.08	49.55	0.28
Poplar	Non-irrigated	1.97	0.09	48.02	0.26
Willow	Non-irrigated	2.42	0.09	47.86	0.13
Eucalyptus	Irrigated	1.81	0.05	50.35	0.39
Poplar	Irrigated	2.23	0.08	48.92	0.14
Willow	Irrigated	2.81	0.08	48.61	0.11

López, E., Pardo, I., & Felpeto, N. (2001). Seasonal differences in green leaf breakdown and nutrient content of deciduous and evergreen tree species and grass in a granitic headwater stream. *Hydrobiologia*, 464(1), 51-61.

Comparable leaf N contents were reported for poplar and eucalyptus by Lopez et al (2001); 2.52 ± 0.08 % of N for poplar and 1.57 ± 0.14 % of N for eucalyptus in spring. However, for P, Lopez et al reported different leaf contents; 0.36 ± 0.01 % of P for poplar and 0.02 ± 0.00 % of P for eucalyptus, therefore P contents measured in Cranfield were low but still in the same range.

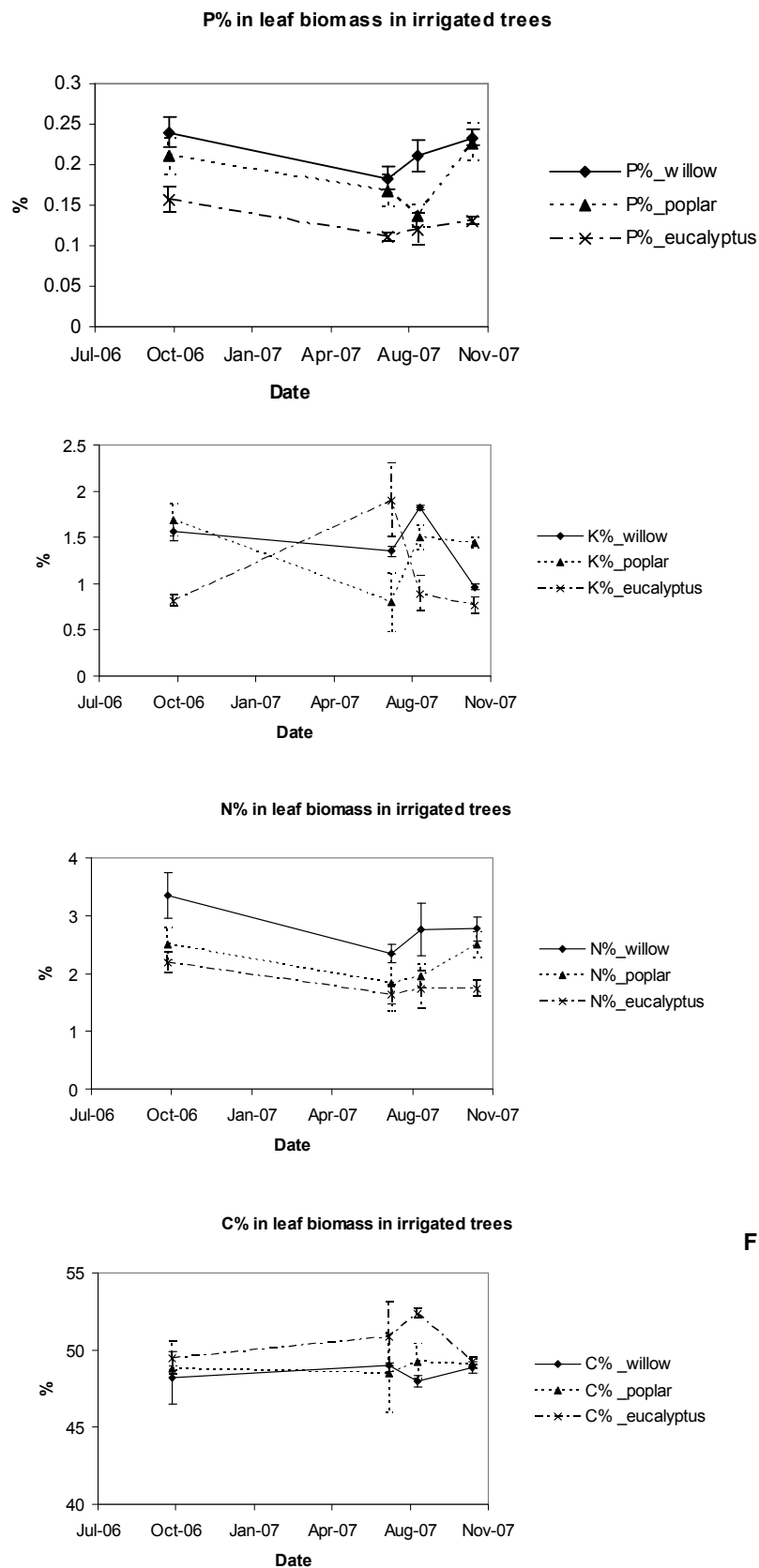


Figure 13
Comparison of nutrient concentration in oven dry leaf biomass of willow, poplar and eucalyptus, under irrigation or non-irrigation. (% oven dry weight)

3.4.1.2 Wood biomass composition

N, P K (in % of wood biomass) data did not need to be transformed to ensure residuals normal distribution.

The results are presented in ANOVA tables (Table 12 for leaf and 14 for wood)

Table 15 ANOVA table for N, P, K, C (%) in wood material from both irrigated and non-irrigated willow, poplar, eucalyptus (in bold, significant factors, $p < 0.05$)

	Degree. of Freedom	N_% - F-	N_% - p-	C_% - F-	C_% - p-
Intercept	1	645.64	0.00	475438.2	0.00
Date(Tree*Irrigation)	6	0.00	1.00	0.0	1.00
Tree	2	4.29	0.04	36.7	0.00
Irrigation	1	20.72	0.00	0.1	0.77
Tree*Irrigation	2	0.01	0.99	1.2	0.34
Error	12				
Total	23				
	Degree. of Freedom	P_% - F-	P_% - p-	K_% - F-	K_% - p-
Intercept	1	1331.22	0.00	1371.07	0.00
Date(Tree*Irrigation)	6	0.030	1.00	0.00	1.00
Tree	2	6.15	0.01	66.20	0.00
Irrigation	1	40.32	0.00	3.07	0.11
Tree*Irrigation	2	2.66	0.11	2.37	0.14
Error	12				
Total	23				

Nutrient content in wood was not significantly affected by the tree's stage of development for all trees (Table 14, $p > 0.05$ for N, P, K and C). Then, concentrations of nutrients were dependent on tree species significantly (Table 14, $p < 0.05$ for N, P, K and C).

For N and P, irrigation increased significantly their concentrations in wood biomass.

For N, K and C concentrations, the order of concentrations were the same for irrigated and non-irrigated trees. For both irrigated and non-irrigated trees, N concentration in wood was classified as following, $N_{\%poplar} > N_{\%eucalyptus} > N_{\%willow}$. For both irrigated and non-irrigated trees, K concentration in wood was classified as follow, $K_{\%eucalyptus} > K_{\%poplar} > K_{\%willow}$. For both irrigated and non-irrigated trees, C concentration in wood was classified as follow, $C_{\%poplar} > C_{\%willow} > C_{\%eucalyptus}$.

Table 16 P, K, N, C concentrations (%) in wood of eucalyptus, poplar and willow non-irrigated and irrigated.

<i>Tree</i>	<i>Irrigation</i>	<i>P_% Mean</i>	<i>P_% Std.Err.</i>	<i>K_% Mean</i>	<i>K_% Std.Err.</i>
Eucalyptus	Non-irrigated	0.07	0.00	0.52	0.01
Poplar	Non-irrigated	0.07	0.00	0.41	0.02
Willow	Non-irrigated	0.06	0.00	0.21	0.01
Eucalyptus	Irrigated	0.08	0.00	0.51	0.03
Poplar	Irrigated	0.11	0.00	0.51	0.02
Willow	Irrigated	0.09	0.00	0.24	
<i>Tree</i>	<i>Irrigation</i>	<i>N_% Mean</i>	<i>N_% Std.Err.</i>	<i>C_% Mean</i>	<i>C_% Std.Err.</i>
Eucalyptus	Non-irrigated	0.44	0.04	47.56	0.09
Poplar	Non-irrigated	0.54	0.05	49.28	0.17
Willow	Non-irrigated	0.39	0.03	48.49	0.17
Eucalyptus	Irrigated	0.65	0.02	47.90	0.04
Poplar	Irrigated	0.74	0.04	49.12	0.06
Willow	Irrigated	0.58	0.04	48.42	0.12

3.4.2 Nutrient uptake, nutrient use efficiency in wood and leaf

3.4.2.1 Nutrient uptake by leaf biomass

N, P K (in odt.ha⁻¹ of foliar biomass) data did not need to be transformed to ensure residuals normal distribution.

The results are presented in ANOVA tables (Table 16 for leaf)

Table 17 ANOVA table for N, P, K, C (odt.ha⁻¹) in leaf material from both irrigated and non-irrigated willow, poplar, eucalyptus (in bold, significant factors, p<0.05)

	<i>Degree. of Freedom</i>	<i>P_odt.ha⁻¹ - F-</i>	<i>P_odt.ha⁻¹ - p-</i>	<i>K_odt.ha⁻¹ - F-</i>	<i>K_odt.ha⁻¹ - p-</i>
Intercept	1	4659.09	0.00	5321.36	0.00
Date(Tree*Irrigation)	14	123.02	0.00	107.85	0.00
Tree	2	115.51	0.00	84.19	0.00
Irrigation	1	22.21	0.00	6.28	0.01
Tree*Irrigation	2	1.61	0.20	23.92	0.00
Error	538				
Total	557				
	<i>Degree. of Freedom</i>	<i>N_odt.ha⁻¹ - F-</i>	<i>N_odt.ha⁻¹ - p-</i>	<i>C_odt.ha⁻¹ - F-</i>	<i>C_odt.ha⁻¹ - p-</i>
Intercept	1	5271.45	0.00	8145.19	0.00
Date(Tree*Irrigation)	14	127.88	0.00	201.34	0.00
Tree	2	164.07	0.00	362.44	0.00
Irrigation	1	6.52	0.01	1.47	0.23
Tree*Irrigation	2	2.91	0.06	2.99	0.05
Error	538				
Total	557				

There was a significant effect of seasonality in leaf nutrient uptake, essentially because willow and poplar are losing their leaves during winter. And yield influenced significantly leaf nutrient's uptake. For all of them, eucalyptus uptake was greater than for willow, whose uptake in turn exceeded that of poplar (Table 17). Moreover, irrigation had a significant effect on uptakes, probably through yield as well and irrigated trees uptakes were significantly higher than non-irrigated trees ones.

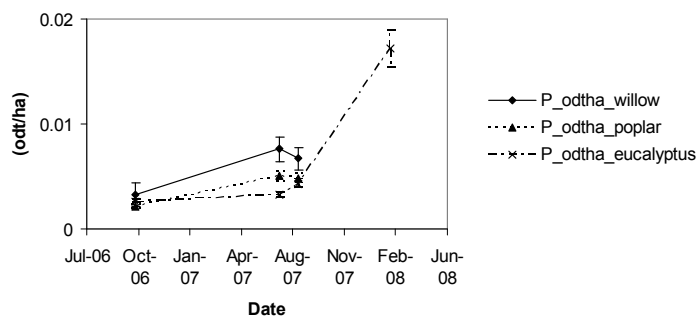
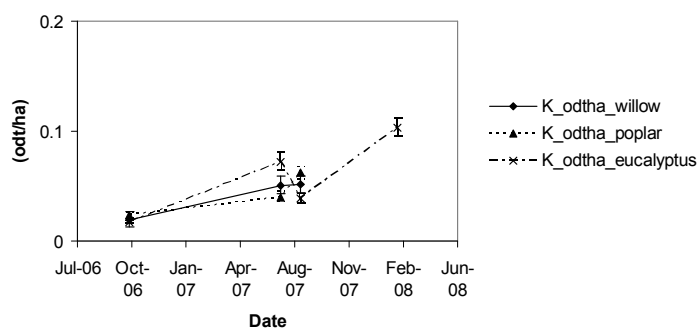
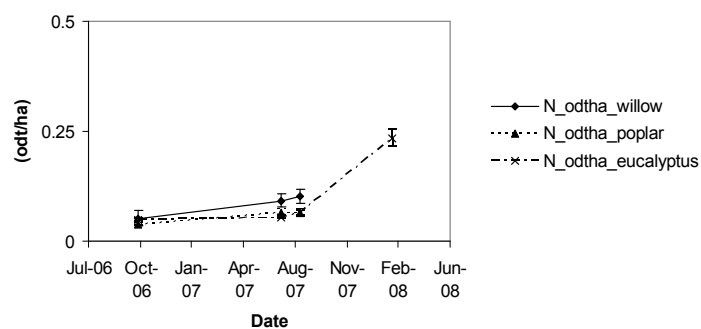
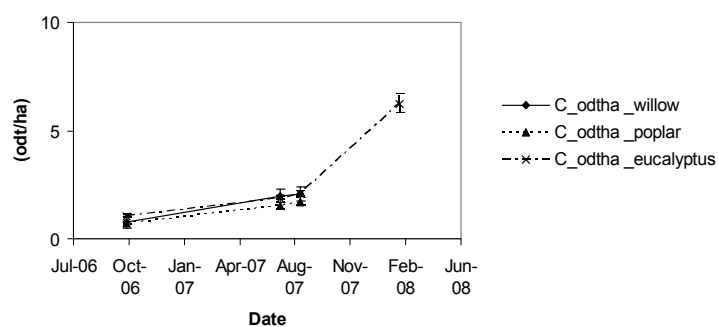
Table 18 Nutrients uptakes per tree species, irrigated or not, in February 2008 in leaf biomass (mean± standard deviation) and total amounts of N, P and K applied during the whole experiment.

Tree	Irrigation	N (kg.ha ⁻¹)	P (kg.ha ⁻¹)	K (kg.ha ⁻¹)	C (odt.ha ⁻¹)	N applied (kg.ha ⁻¹)	P applied (kg.ha ⁻¹)	K applied (kg.ha ⁻¹)
Eucalyptus	NO	213.5±10.4	13.8±0.5	140.8±11.1	16.68±0.03	0	0	0
Poplar	NO	69.1±3.1	5.8±0.3	52.7±1.7	7.80±0.03	0	0	0
Willow	NO	105.5±3.9	8.0±0.2	49.9±0.9	4.86±0.01	0	0	0
Eucalyptus	YES	230.3±6.6	16.4±0.7	134.5±12.2	4.20±0.01	814	82	548
Poplar	YES	74.7±2.8	6.4±0.3	45.7±2.3	19.46±0.02	632	63	426
Willow	YES	117.4±3.3	9.2±0.2	55.9±0.4	11.20±0.03	851	86	573

The proportions of nutrients applied uptaken in the leaves are presented in Table 18. For N and P, eucalyptus leaves took up in proportion almost twice more the amounts of nutrients applied than poplar and willow leaves. However, they were of the same order of magnitude for K.

Table 19 Proportion of nutrients applied effectively uptaken in leaf biomass (%) for irrigated trees.

	N	P	K
Eucalyptus	28	20	6
Poplar	12	10	11
Willow	14	10	10

P_{odt}/ha in leaf biomass in non-irrigated trees**K_{odt} in leaf biomass in non-irrigated trees****N_{odt} in leaf biomass in non-irrigated trees****C_{odt} in leaf biomass in non-irrigated trees**

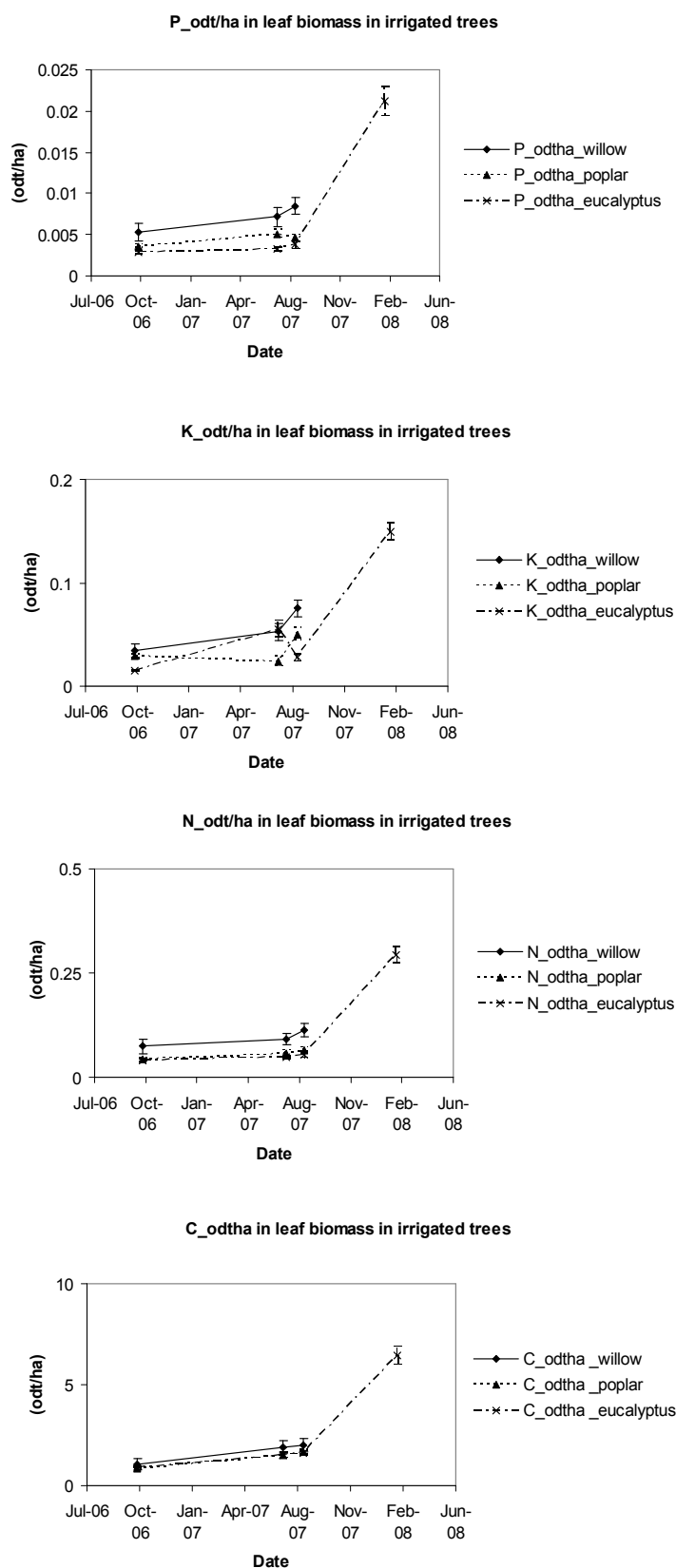


Figure 14 Evolution of foliar biomass ($\text{odt} \cdot \text{ha}^{-1}$) from October 2006 to October 2007 in willow, poplar and eucalyptus irrigated and non-irrigated.

3.4.2.2 Nutrient uptake by wood biomass

N, P K, C (in odt.ha^{-1} of wood biomass) data did not need to be transformed to ensure residuals normal distribution.

The results are presenting in ANOVA tables (Table 19)

Table 20 ANOVA table for N, P, K, C (odt.ha^{-1}) in wood material from both irrigated and non-irrigated willow, poplar, eucalyptus (in bold, significant factors, $p < 0.05$)

	<i>Degree. of Freedom</i>	<i>P_ odt.ha⁻¹ - F-</i>	<i>P_ odt.ha⁻¹ - p-</i>	<i>K_ odt.ha⁻¹ - F-</i>	<i>K_ odt.ha⁻¹ - p-</i>
Intercept	1	3704.08	0.00	3584.28	0.00
Tree	2	365.43	0.00	905.88	0.00
Irrigation	1	227.87	0.00	25.32	0.00
Tree*Irrigation	2	18.12	0.00	5.92	0.00
Error	174				
Total	179				
	<i>Degree. of Freedom</i>	<i>N_ odt.ha⁻¹ - F-</i>	<i>N_ odt.ha⁻¹ - p-</i>	<i>C_ odt.ha⁻¹ - F-</i>	<i>C_ odt.ha⁻¹ - p-</i>
Intercept	1	3147.84	0.00	3152.42	0.00
Tree	2	358.21	0.00	445.02	0.00
Irrigation	1	244.47	0.00	21.93	0.00
Tree*Irrigation	2	30.69	0.00	16.67	0.00
Error	174				
Total	179				

N, P, K uptakes (odt.ha^{-1}) and C productions were significantly different by tree species. Biomasses did influence more than nutrients concentrations because for all nutrients, the order of the amounts uptaken was the same as the biomass production order: $\text{uptake}_{\text{eucalyptus}} > \text{uptake}_{\text{willow}} > \text{uptake}_{\text{poplar}}$. And for all nutrients, uptakes were significantly greater for irrigated trees than non-irrigated trees, probably because yields were greater under irrigation.

For willow N uptakes, both values (non-irrigated $63.2 \pm 4.6 \text{ kg.ha}^{-1}$ and irrigated $134.7 \pm 9.5 \text{ kg.ha}^{-1}$) were within values reported in the literature ($64\text{--}149 \text{ kg.ha}^{-1}$ for the second growing season (Aronsson and Bergstrom, 2001)).

Table 21 Nutrients uptakes per tree species, irrigated or not, in February 2008 in wood biomass (mean± standard deviation)

Tree	Irriga- tion	P (kg.ha ⁻¹)	K (kg.ha ⁻¹)	N (kg.ha ⁻¹)	M _{wood} (odt.ha ⁻¹)
Eucalyptus	No	23.2±1.7	182.0±4.9	154.4±13.7	35.1±3.7
Poplar	No	6.0±0.3	34.6±1.4	46.0±4.3	8.5±2.3
Willow	No	9.2±0.4	34.3±2.0	63.2±4.6	16.1±6.8
Eucalyptus	Yes	32.4±0.1	205.3±13.8	262.4±8.4	40.6±4.9
Poplar	Yes	10.6±0.5	50.0±1.7	73.6±4.0	9.9±2.4
Willow	Yes	20.7±0.9	55.4±0.0	134.7±9.5	23.1±4.3

The total amount of nutrients uptaken in both leaf and wood biomass were calculated and the proportions they represent compared to the total amount of nutrients applied are presented in Table 21. Again, eucalyptus trees took up twice more in proportion and in amounts than willow and poplar.

Table 22 Nutrients uptakes per irrigated tree species, irrigated or not, in February 2008 in leaf and wood biomass, total amounts of N, P and K applied during the whole experiment and % nutrient uptaken compared to nutrient amount applied.

	<i>Eucalyptus</i>	<i>Poplar</i>	<i>Willow</i>
N_total uptaken (kg.ha ⁻¹)	492	149	252
P_total uptaken (kg.ha ⁻¹)	48	17	30
K_total uptaken (kg.ha ⁻¹)	240	96	111
N applied (kg.ha ⁻¹)	814	632	851
P applied (kg.ha ⁻¹)	82	63	86
K applied (kg.ha ⁻¹)	548	426	573
N (%)	60	24	30
P (%)	59	27	35
K (%)	44	23	19

Comparisons with other values reported in the literature (Table 22, Paranychianakis et al., (2006) revealed that for willow, yield were low (23.1 odt.ha⁻¹ compared to 35 odt.ha⁻¹) but the percentage of N in wood mass were close (17 % for Cranfield and 16 % for Labrecque and Teodorescu, (2003) with the same cultivar but may be not same clone) and for P (8 % for Cranfield, and 9 % for Labrecque and Teodorescu, (2003)). The low yield might be explained either as a stress response to the field condition. However irrigation increased significantly yield hence, it might reveal bad climato-edaphic conditions for willow growth. *S.viminalis* yield in Cranfield was low

even compared to yields reported by Aylott et al. (2008) of $25 \pm 2.1 \text{ odt.ha}^{-1}$ and $30.36 \pm 0.90 \text{ odt.ha}^{-1}$ for 2 clones of *S.viminalis* from an English cultivars (Aylott et al., 2008). Moreover, yields reported by Aronsson et al. (2001) for *S.viminalis* grown in lysimeters planted at the density of 20,000 trees.ha⁻¹ (Cranfield density is 13,060 trees.ha⁻¹) were of 1.6-19.8-27.4 odt.ha⁻¹ for Year 1, 2 and 3.

For poplar, yields were higher for Cranfield (8.5 and 9.9 odt.ha⁻¹) than yield reported by Moffat et al. (2001); 2.19 to 5.45 odt.ha⁻¹. As in Cranfield, clusters of five stems were planted from Year 1, this was done to mimic a year one sprouted stem but it might influence positively biomass yield. But Cranfield poplar yields were lower than yields reported for Trichobel (*P.trichocarpa* x *P.trichocarpa*, same clone as in Cranfield) by Aylott et al (2008) $9.08 \pm 0.75 \text{ odt.ha}^{-1} \cdot \text{year}^{-1}$ (Aylott et al., 2008). In terms of N and P content, Cranfield were comparable for irrigated plots to (Moffat et al., 2001/3) values. But as yields are greater, concentrations are lower for Cranfield.

For eucalyptus, Cranfield yields were comparable to the different eucalyptus species studied by Guo et al., (2002) (35.1 and 40.6 odt.ha⁻¹ for Cranfield against 39.7 to 45.5 odt.ha⁻¹ for Guo). But for *E.gunnii* (Hardcastle, 2006) reported yield of 9 odt.ha⁻¹ .year⁻¹ and rotation of 8 years, then Cranfield yields appeared to be good as 1.95 times greater for non irrigated and 2.25 times greater for irrigated trees. N and P concentrations were slightly lower 154.4 and 262 kg.ha⁻¹ for Cranfield against 425 and 401 kg.ha⁻¹ for (Guo et al., 2002) for N and 23 and 32 kg.ha⁻¹ for Cranfield against 42 and 37 kg.ha⁻¹ for P (Guo et al., 2002).

Hence yield and nutrient concentrations for willow and eucalyptus are comparable to the one reported in the literature, however, for poplar, they are slightly different, with greater yield and greater dilution of nutrients in biomass.

Table 23 Potential of biomass production and nutrient (nitrogen and phosphorus) removal of plant species. (Source: Paranychianakis et al., 2006).

Plant species	Age of crop	Biomass (t/ha)	N removal (kg/ha)	P removal (kg/ha)	Reference
<i>Eucalyptus botryoides</i>	3	39.7	425	42	Guo et al. (2002)(i)
<i>Eucalyptus ovata</i>	3	45.5	401	37	Guo et al. (2002)
<i>Populus trichocarpa</i>	3	2.19 to 5.45*	72.9	11.2	Moffat et al. (2001)
<i>Salix viminalis</i> (hybrid willow) 1 st rotation	3	35.08	232	27.5	Labrecque and Teodorescu (2003)

*Biomass assessed after leaf fall.

3.4.3 Nutrient use efficiency

Performance of a WaterRenew system lies partly on the aptitude of the soil-plant system to uptake nutrients. For this reason, nutrient use efficiencies were calculated and compared for the 3 tree species irrigated or not.

Nutrient use efficiency (NUE) is defined by equation 15; i.e. the mass of biomass produced by mass of a particular nutrient (van Wijk et al., 2003).

$$NUE = \frac{\text{mass of dry matter (g)}}{\text{mass of nutrient (g)}} \quad \text{Equation 15}$$

Average nutrient removals were calculated as the amount of nutrient constituting tree biomass. Because willow and poplar lose their leaves in autumn unlike eucalyptus, nutrients use efficiencies were calculated for wood (willow, poplar and eucalyptus, irrigated or not) and reported in Table 22.

For all trees and treatments, NUE for P were higher than NUE_K and finally both being greater than NUE_N. In other word, more unit of biomass was produced per unit of P, K and N respectively.

There was a difference of NUE for irrigated and non-irrigated trees. Willow and eucalyptus non-irrigated trees NUE were greater for P (1.62 times and 1.28 respectively, Table 22) and N (1.69 times and 1.08 respectively) than for irrigated trees. It means less P and N in non-irrigated eucalyptus led to the production of the same amount of biomass in irrigated trees. As irrigation with secondary treated effluent was also providing N, P and K to trees, these higher NUE for non-irrigated trees revealed a luxury consumption¹ (van Wijk et al., 2003) of N and P. Hence, in terms of a WaterRenew system performance, these luxury consumptions are to be encouraged as it means more nutrients are consumed to produce the same amount of biomass, therefore encouraging nutrients' uptake from effluent.

For poplar trees, for all macronutrients, irrigated poplars presented higher NUE than non-irrigated trees (P: 1.39 times, N: 2.38 and K: 1.64 respectively), i.e. for irrigated trees, less N, P and K led to the production of the same amount of biomass than non-irrigated trees.

¹ Luxury consumption of nutrients: "the absorbance of nutrients in excess of the immediate plant growth requirements" (van Wijk et al., 2003)

These NUE were compared to values in the literature (van Wijk et al., 2003; Johnstone et al., 1934.). In general, NUE calculated for the Cranfield field trial were lower than NUE reported in the literature (Table 22), especially for irrigated trees. This probably reflects nutrient luxury consumption (van Wijk et al., 2003). However, eucalyptus non-irrigated NUE_P (1510>1429, van Wijk et al., 2003) and willow non-irrigated NUE_K (470>350, (van Wijk et al., 2003)) were greater than values reported hence, these trees were better performing than others but not significantly (cf. standard deviations in Table 22).

Table 24 NUE, nutrient use efficiencies for wood only after 2 years of cultivation for willow, poplar and eucalyptus irrigated or not. (¹ values from (van Wijk et al., 2003) for forest wood chips. (Mean \pm standard deviation)

Tree	Irrigation	NUE_P	NUE_P ¹	NUE_K	NUE_K ¹
Willow	Non-irrigated	1510 \pm 2254	909-1429	193 \pm 756	323-500
Poplar	Non-irrigated	1254 \pm 42905	1000-2000	198 \pm 357	256-370
Eucalyptus	Non-irrigated	1422 \pm 6547	3477	246 \pm 1581	427
Willow	Irrigated	933 \pm 5147	909-1429	198 \pm 1439	323-500
Poplar	Irrigated	1742 \pm 17213	1000-2000	470 \pm 3414	256-370
Eucalyptus	Irrigated	1115 \pm 4563	3477	418	427

Tree	Irrigation	NUE_N	NUE_N ¹
Willow	Non-irrigated	227 \pm 274	152-244
Poplar	Non-irrigated	155 \pm 588	145-370
Eucalyptus	Non-irrigated	185 \pm 526	219
Willow	Irrigated	134 \pm 606	152-244
Poplar	Irrigated	255 \pm 1471	145-370
Eucalyptus	Irrigated	172 \pm 457	219

4. CONCLUSIONS

The conclusions regarding trees on the 2 years trial of a WaterRenew system irrigated with secondary treated effluent at Cranfield University can answer the objectives of this chapter as follows:

- **Objective 1:** focused on SRC mass productions:
 - 1) First of all, irrigation increased yield significantly for the 3 tree species studied, *S.viminalis* (+1.43 times with irrigation), *P. trichocarpa* (+1.16 times with irrigation) and *E.gunnii* (+1.16 times with irrigation). During January 2008, the sys-

tem was irrigated manually to deliver 758 mm for willow plots, 768 mm for poplar, and 606 mm for eucalyptus plots, these values are for a month. These applications corresponded to an N application of 139 kg-N.ha^{-1} , 140 kg-N.ha^{-1} , 102 kg-N.ha^{-1} for willow, poplar and eucalyptus respectively. Therefore, per year, these applications correspond to $1,668 \text{ kg-N.ha}^{-1}.\text{yr}^{-1}$, $1,680 \text{ kg-N.ha}^{-1}.\text{yr}^{-1}$ and $1,224 \text{ kg-N.ha}^{-1}.\text{yr}^{-1}$ for willow, poplar and eucalyptus respectively. These applications are very high on both an hydraulic loads point of view than on the N application loads, almost 6 times more than the maximum N application allowed of $250 \text{ kg-N.ha}^{-1}.\text{yr}^{-1}$ for NVZ. But, in spite of these high hydraulic and N loads, yields remained within the averages reported in the literature for willow and eucalyptus; 35 odt.ha^{-1} for irrigated willow within the average range of 15-27 odt.ha^{-1} for the first rotation (DEFRA, 2002.) and 40.6 odt.ha^{-1} for irrigated eucalyptus greater than 24 odt.ha^{-1} for the average *E.gunnii* after 3 years (Hardcastle, 2006). For poplar, yields were in the range of the literature average for the same species but not greater. Cranfield poplar irrigated yield was 17 odt.ha^{-1} after the first rotation against the 15-27 odt.ha^{-1} (DEFRA, 2002.). However, as the irrigated yields were greater than the non-irrigated ones, these average yields are more likely to reflect the field conditions rather than an irrigation stress effect. As the trial was lying on a very heavy clay, this edapho-climatic conditions were more limiting for tree development than irrigation with effluent. In particular there was no reduction in yield related to Na stress as over $1.9 \text{ ton-Na.ha}^{-1}$, $1.5 \text{ ton-Na.ha}^{-1}$ $1.6 \text{ ton-Na.ha}^{-1}$ were applied during the experimentation on willows, poplar and eucalyptus respectively.

- 2) Regarding comparisons of yields between tree species, eucalyptus trees performed the best (1.75 times greater than willow yield, 4.1 times greater than poplar yield). Moreover, eucalyptus wood densities calculated from the data set were almost twofold greater than those of poplar and willow. As density is proportional to FVI, from a wood production point of view, eucalyptus seems to be the best species.

- **Objective 2:** In terms of SRC water-use and WaterRenew system:

- 1) As the irrigation system was triggered by soil moisture, willow trees took up the greatest amount of effluent, as they received the greatest amount of effluent (3625 mm over the 2 years, 2895 mm for poplar and 3345 mm for eucalyptus).
- 2) Compared to willow and eucalyptus trees, poplar trees were slower to start off

at the beginning of the experiment, however, from the second year, poplars' uptake rate was comparable to eucalyptus and willow ones. Hence, for a WaterRenew perspective, with poplar, less volume of effluent can be applied during the first year.

- 3) Comparisons of water-use between tree species: Eucalyptus trees' water use efficiency (WUE) was 2.9 greater than willow (1.39) and poplar (1.08). But from a WaterRenew point of view, a low WUE is preferred as it means more water needs to be transpired in order to produce the same amount of biomass; hence more water can be applied, hence treated. Of course, WUE is to be considered with the amount irrigated, hence, willow in this perspective seems to be the best performing species as receiving the greatest amount of effluent and having an average WUE compared to the other species.

- **Objective 3:** SRC nutrient uptake and WaterRenew system point of view:

- 1) Nutrients were applied as constituents of the secondary treated effluent, hence the more effluent that was irrigated, the more nutrients that were applied. Therefore, willow received the greatest amount of nutrients; 1023 kg-N.ha⁻¹ and 134 kg-P.ha⁻¹ for willow, 834 kg-N.ha⁻¹ and 108 kg-P.ha⁻¹ for poplar and 946 kg-N.ha⁻¹ and 127 kg-P.ha⁻¹ for eucalyptus for the 2 years of irrigation.
- 2) Comparisons of the nutrients' uptake between tree species: poplar presented the greatest NUE (nutrient use efficiency, dry mass (g)/ nutrient content (g)), for both N and P (255, 1742 against 172, 1115 for eucalyptus and 134, 933 for willow respectively). But poplar yield was the lowest so that in terms of net nutrients uptakes, poplars were the least performing (74 kg-N.ha⁻¹.yr⁻¹, 11 kg-P.ha⁻¹.yr⁻¹ against 135 kg-N.ha⁻¹.yr⁻¹, 21 kg-P.ha⁻¹.yr⁻¹ for willow and 262 kg-N.ha⁻¹.yr⁻¹, 32 kg-P.ha⁻¹.yr⁻¹ for willow). Therefore, again, eucalyptus was the best performing specie.

Hence, for both yields and nutrients points of view, eucalyptus trees performed the best. And for a WaterRenew system perspective, eucalyptus performed the best as well as it corresponded to a balance between water use and nutrients uptake. But eucalyptus keeps its leaves year long. Leaves need to be dried before being considered to be eventually used as biofuel. Therefore, this leaf mass corresponds to an additional mass that needs to be transported and dried with potentially no economical benefit.

However, in this chapter, only the tree compartment of the system was considered. But as reflected in Figure 1, a WaterRenew system is constituted of soil, water and plant. Therefore, nutrients dynamics with other compartments are considered in the following chapters as the fate of applied nutrients has to be determined to conclude on nutrients removal efficiency.

5. REFERENCES

- Allen, R. G. (1998.), *Crop evapotranspiration: guidelines for computing crop water requirements*, Food and Agriculture Organization of the United Nations, Rome.
- Aronsson, P. G. and Bergstrom, L. F. (2001/3), "Nitrate leaching from lysimeter-grown short-rotation willow coppice in relation to N-application, irrigation and soil type", *Biomass and Bioenergy*, vol. 21, no. 3, pp. 155-164.
- Aronsson, P. G., Bergstrom, L. F. and Elowson, S. N. E. (2000/2), "Long-term influence of intensively cultured short-rotation Willow Coppice on nitrogen concentrations in groundwater", *Journal of Environmental Management*, vol. 58, no. 2, pp. 135-145.
- Aylott, M. J., Casella, E., Tubby, I., Street, N. R., Smith, P. and Taylor, G. (2008), "Yield and spatial supply of bioenergy poplar and willow short-rotation coppice in the UK", *New Phytologist*, vol. 178, no. 2, pp. 358-370.
- BERR (2008), "UK renewable energy strategy: consultation document", *Department of Business, Enterprise and Regulatory Reform*.
- Castelan-Estrada, M., Vivin, P., & Gaudillere, J. P. (2002). Allometric relationships to estimate seasonal above ground vegetative and reproductive biomass of vitis vinifera L. *Annals of Botany*, 89, 401-408.
- Crow, P. and Houston, T. J. (2004), "The influence of soil and coppice cycle on the rooting habit of short rotation poplar and willow coppice", *Biomass and Bioenergy*, vol. 26, no. 6, pp. 497-505.
- Darcy, H. (1856), "Les Fontaines Publiques de la Ville de Dijon", .
- DEFRA (2002.), *Growing short rotation coppice : best practice guidelines for applicants to DEFRA's energy crops scheme*. DEFRA, London.
- Dutilleul, P., Herman, M. and Avella-Shaw, T. (1998), " Growth rate effects on correlations among ring width, wood density, and mean tracheid length in Norway spruce (*Picea abies*) ", *Canadian Journal of Forest Research*, vol. 28, no. 1, pp. 56-68.
- Ehlers, W. and Goss, M. (. (2003), "Water Dynamics in Plant Production.", *Wallingford: CABI Publishing.*, , pp. 273 pp.
- Elowson, S. and Rytter, L. (1984), "Biomass distribution within willow plants growing on a peat bog.", *Ecology and Management of Forest Biomass. Production Systems Dept. of Ecol. and Environ. Res. , Swed. Univ. Agric. Sci. Rep.*, , no. 15, pp. 325-334.
- Forestry Commission. (1975.), *Forest mensuration handbook*, H.M.S.O., London.

- GB, Parliament. Joint Committee on Statutory Instruments. (2008), *Action Programme for Nitrate Vulnerable Zones (England and Wales) Regulations 2008*. Great Britain. Parliament. House of Commons.; Great Britain. Parliament. House of Lords.(draft for consultation), The Stationery Office.
- Guo, L. B., Sims, R. E. H. and Horne, D. J. (2002), "Biomass production and nutrient cycling in Eucalyptus short rotation energy forests in New Zealand. - I: biomass and nutrient accumulation.", *Bioresource Technology*, vol. 85, no. 3, pp. 273-283.
- Hardcastle, P. D. (2006), "A Review of the Potential Impacts of Short Rotation Forestry, Final Report", .
- Heilman, P. E., Ekuan, G. and Fogle, D. (1994), "Above-ground and below-ground biomass and fine roots of 4-year-old hybrids of *Populus trichocarpa* X *Populus deltoides* and parental species in short-rotation culture", *Canadian Journal of Forest Research*, vol. 24, no. 6, pp. 1186-1192.
- Hillel, D. (1980), *Applications of Soil Physics*. Academic Press.
- Kirui, B., Kairo, J. G., & Karachi, M. (2006). Allometric equations for estimating above ground biomass of *rhizophora mucronata* lamk (rhizophoraceae) mangroves at gazi bay, kenya. *Western Indian Ocean J.Mar. Sci.*, 5(1), 27-34.
- Johnstone, J., 1870-1932., Daniel, R. J., University of Liverpool. Lancashire Sea-Fisheries Laboratory. and Redfield, R. (1934.), *James Johnstone memorial volume*, University Press of Liverpool, [Liverpool].
- Jørgensen, S. E. and Endoricchio, G. (2001), "Fundamentals of ecological modelling. 3rd edition", vol. 21, pp. 1-530.
- Kettlewell, P., Atkinson, M., Stephenson, D., Easey, J. and Hollins, P. (2003), "Potential predictability of soil moisture deficit in britain from the north atlantic oscillation", *Geophysical Research Abstracts*, vol. 5, pp. 12222.
- Klasnja, B., Kopitovic, S. and Orlovic, S. (2002), "Wood and bark of some poplar and willow clones as fuelwood", *Biomass and Bioenergy*, vol. 23, no. 6, pp. 427-432.
- Labrecque, M. and Teodorescu, T. I. (2003), "High biomass yield achieved by *Salix* clones in SRIC following two 3-year coppice rotations on abandoned farmland in southern Quebec, Canada", *Biomass and Bioenergy*, vol. 25, no. 2, pp. 135-146.
- Le Roux, D., Stock, W. D., Bond, W. J. and Maphanga, D. (1996), "Dry mass allocation, water use efficiency and $\delta^{13}\text{C}$ in clones of *Eucalyptus grandis*, *E. grandis* x *camaldulensis* and *E. grandis* x *nitens* grown under two irrigation regimes", *Tree Physiology*, vol. 16, pp. 497-502.
- Li, C. (2000), "Population differences in water-use efficiency of *Eucalyptus microtheca* seedlings under different watering regimes", *Physiologia Plantarum*, vol. 108, no. 6, pp. 134-139.
- Liang, Z., Yang, J., Shao, H. and Han, R. (2006), "Investigation on water consumption characteristics and water use efficiency of poplar under soil water deficits on the Loess Plateau", *Colloids and Surfaces B: Biointerfaces*, vol. 53, no. 1, pp. 23-28.
- Lindroth A. and Cienciala E. (1996), "Water use efficiency of short-rotation *Salix viminalis* at leaf, tree and stand scales", *Tree Physiology*, vol. 16, pp. 257-262.

- López, E., Pardo, I., & Felpeto, N. (2001). Seasonal differences in green leaf breakdown and nutrient content of deciduous and evergreen tree species and grass in a granitic headwater stream. *Hydrobiologia*, 464(1), 51-61.
- MAFF, (2000), *Fertiliser recommendations for agricultural and horticultural crops (RB209)*, Seventh edition ed., the stationary office, London, UK.
- MAFF (1986.), *The analysis of agricultural materials : a manual of the analytical methods used by the Agricultural Development and Advisory Service*, 3rd ed, HMSO, London.
- Martin, P. J. and Stephens, W. (2006/2), "Willow growth in response to nutrients and moisture on a clay landfill cap soil. II: Water use", *Bioresource Technology*, vol. 97, no. 3, pp. 449-458.
- McBean, E. A. and Rovers, F. A. (1998), *Statistical procedures for analysis of environmental monitoring data and risk assessment*, Prentice Hall PTR, Upper Saddle River, N.J.
- Miranda, I., Almeida, M. H. and Pereira, H. (2001), "Provenance and site variation of wood density in *Eucalyptus globulus* Labill. at harvest age and its relation to a non-destructive early assessment", *Forest Ecology and Management*, vol. 149, no. 1-3, pp. 235-240.
- Moffat, A. J., Armstrong, A. T. and Ockleston, J. (2001/3), "The optimization of sewage sludge and effluent disposal on energy crops of short rotation hybrid poplar", *Biomass and Bioenergy*, vol. 20, no. 3, pp. 161-169.
- Myers B.J., Theiveyanathan S., O'Brien N. D. and Bond W. J. (1996), "Growth and water use of *Eucalyptus grandis* and *Pinus radiata* plantations irrigated with effluent", *Tree Physiology*, vol. 16, pp. 211-219.
- Myers, B. J., Bond, W. J., Benyon, R. G., Falkiner, R. A., Polglase, P. J., Smith, P. J., Snow, V. O. and Theiveyanathan, S. (1999), "Sustainable Effluent-Irrigated Plantations: An Australian Guideline", *CSIRO Forestry and Forest Products*, .
- Paranychianakis, N. V., Angelakis, A. N., Leverenz, H. and Tchobanoglous, G. (2006), "Treatment of Wastewater With Slow Rate Systems: A Review of Treatment Processes and Plant Functions", in *Critical Reviews in Environmental Science and Technology*. Boca Raton: 2006. Vol. 36, Iss. 3 and pg. 187, 7. p. (eds.) , pp. 187-260.
- Pliura, A., Zhang, S. Y., MacKay, J. and Bousquet, J. (2007), "Genotypic variation in wood density and growth traits of poplar hybrids at four clonal trials", *Forest Ecology and Management*, vol. 238, no. 1-3, pp. 92-106.
- Stephens, W., Hess, T. and Knox, J. (2001a), "Review of the effects of energy crops on hydrology, Report to MAFF by", *Report MAFF*, vol. NF0416.
- Stephens, W., Hess, T. and Knox, J. (2001b), *Review of the effects of energy crops on hydrology*, 1, Insitute of Water and Environment, Cranfield University, Silsoe, MK454DT, UK, Insitute of Water and Environment, Cranfield University, Silsoe, MK454DT, UK.
- van Wijk, M. T., Williams, M., Gough, L., Hobbie, S. E. and Shaver, G. R. (2003), "Luxury consumption of soil nutrients: a possible competitive strategy in above-ground and below-ground biomass allocation and root morphology for slow-growing arctic vegetation?", *Journal of Ecology*, vol. 91, no. 13, pp. 664-676.

Volk, T. A., Abrahamson, L. P. and White, E. H. (2001), "Root Dynamics in Willow Biomass Crops.", *Interim report prepared for the United States Department of Energy under cooperative agreement*, vol. No. DE-FC36-96GO10132.

CHAPTER 5 : CHANGES IN SOIL CHEMISTRY IN EFFLUENT IRRIGATED WILLOW, POPLAR, EUCALYPTS PLANTED FIELD TRIAL

1. INTRODUCTION

This chapter presents an investigation into the effect of implementing a WaterRenew system on an SRC site soil dynamics. As this system relies heavily on the soil capacity to transform nutrients (Aronsson and Perttu, 2001), this system focuses in particular on how soil responds to wastewater application and how this response might be affected by tree presence. Moreover, a successful WaterRenew system has to remain sustainable. The system has to remain fertile and usable; physically, soil has to keep a good structure and chemically, nutrients' build up must not be allowed to reach a point where soil could start leaching nutrients excessively. For these reasons, there was a particular emphasis on soil evolution during the whole experiment and that was why soil was analysed. Details were provided about firstly, the effluent used for irrigation and the corresponding nutrients amount applied, then details about the evolution of particular nutrients in soil, processes involved and the end states of soil after irrigation in a WaterRenew system. Effluent and soil properties were evaluated through laboratory analysis and the methodology followed to sample and analyse soil was described in detail in Chapter 3. In effect, the conclusions of a literature review on potential risks associated with running a WaterRenew system (Chapter 2) were identified as phosphorus (Sharpley, 1995) and sodium (Allen, 1998.; Westcot, 1988). They were expected to accumulate in soil, however, during the experiment, it was not known to what extent these accumulations would take place.

The chapter is divided into 3 main parts: methodology, results and discussion and conclusion.

The methodology section in this chapter presents a brief summary of the methods used (sampling, analysis) with reference to Chapter 3. The results and discussion sections were articulated around each of the variables monitored regrouped in soil salinity and soil nutrients dynamics. Finally, the conclusion section gives a comprehensive overview of the effect of the implementation of a water renew system on a SRC under Cranfield soil and climate conditions.

The specific objectives of this soil analysis were to :

- **Objective 1:** Identify and quantify significant changes in soil chemistry as a result of effluent tertiary treatment, i.e. N and P removal. (K removal will be considered as well as essential macronutrient for plant growth).
- **Objective 2:** Identify and quantify possible adverse effects, significant or not on soil chemistry results of a WaterRenew system; in particular P accumulation and salinisation. And understand the processes involved.

This chapter should also test the following hypothesis:

- **Hypothesis:** soil treatment capacity was greater than plant treatment capacity by uptake. Trees capacity to uptake N and P was lower than soil capacity to retain or transform N and P.

2. MATERIAL AND METHODS

2.1 SITE

The site experiment was set up at Cranfield University sewage treatment works (lowland Eastern England, Bedfordshire, UK). The mean annual precipitation was 629 mm; 10.0°C mean annual temperature and an annual average Penman evapotranspiration of 1.4 mm/day (Cranfield University, Silsoe met station, data from 1992-2006).

According to Soil Survey of England and Wales soil map (1993), Cranfield site soil was a Pelosol, a slowly permeable clayey soil.

Pre-irrigation soil samples were collected on February 2006 at 6 depths (10, 30, 50, 100, 150 and 170 cm) over the field. The soil was very fine heavy clay without structure until 110 cm and then chalky heavy clay until 130 cm depth. The average bulk density was 1.22 g/cm³. The soil was assessed according to FAO guidelines for soil evaluation for irrigation (FAO 55, 1985). Cranfield has been located in a nitrate vulnerable zone since 1996 (DEFRA, 2002). For nitrogen (N), the average N content was 0.23 % for the root zone, i.e. in the upper normal range. In RB209, there was no N-index as such but a SNS index (Soil Nitrogen Supply). The SNS was defined as the sum of “soil mineral nitrogen (SMN) in the layer 0-90 cm, the estimate of total crop nitrogen content at time of sampling for SMN and the estimate of organic-N mineralised during the growing season” (MAFF 2000). Moreover, as N fertilisation was not required or advised for year one (Armstrong et al., 2002.), SNS won't be considered furthermore. For

phosphorus (P), response to fertilisation will be unlikely as the extractable P concentration for the root zone was 14.4 mg-P.L^{-1} of dry soil. This concentration was associated to a P-index 1 according to RB 209 (MAFF 2000). The exchangeable potassium, K, concentration for the root zone was 1309 kg/ha (222 mg-K.L^{-1} in the 15 first cm corresponding to a soil K-index of 2 according to RB 209) and therefore it was unlikely to see any crop response to fertilisation ($>300 \text{ kg-K/ha}$). Hence, because of the starting point soil composition (Chapter 3, 2.3), it was unlikely to see any fertilisation effect on tree growth. Therefore, as there was a significant effect of irrigation on tree growth (Chapter 4, 3.2.2), the significant higher yield under irrigation was caused by the additional “water” part of the effluent rather than the “nutrient” part of the effluent.

2.2 TREATMENTS

The field was artificially built and the soil completely disturbed. It was divided into 24 plots of 3.5 m by 3.5 m spaced with a 1 m pathway (Figure 1). Each plot was bounded by a polythene sheet of 60 cm width buried to 50 cm depth to prevent surface runoff or near surface lateral movement. The 24 plots were organised in three replicates randomly distributed, of four covers under two treatments. The covers were: 16 trees of willow (W, *Salix viminalis*), poplar (P, *Populus trichocarpa*), eucalyptus (E, *Eucalyptus gunnii*) at a tree spacing of 1 m, the four inner trees being measurement trees, and an unplanted control, (U). The plots were randomly assigned to be either: irrigated with wastewater (+) or non-irrigated (-) as a control of treatment. Usually, at the end of the first year, mono-stems were cut back to promote sprouting (Aronsson *et al*, 2000). In order to mimic this second year cut back poplars and willows were planted as a cluster of five cuttings in spring 2006.

A computerised drip-irrigation system was set up, with 16 drippers (4 L/hour) per plot from July 2006 until August 2007. Then, in August 2007, the irrigative capacity was doubled from 15mm/day to 30mm/day on installing new drippers.

The main idea of the irrigation system settings was to allow the maximum water application whilst avoiding runoff, minimising drainage and consequently creating well watered favourable conditions for plant growth. For this reason, the irrigation was triggered by soil moisture measurements (soil moisture sensor SM200, Delta T) in the middle of each plot to start when soil moisture content was lower than field capacity. The irrigation started in mid-July 2006 and continued until late December 2006. Then, it was stopped due to water freezing in the pipe work until late February 2007. The second irrigation period lasted from March 2007 until October 2007 but manual doses of effluent were added during winter 2007-2008 until February 2008 when the trees were harvested.

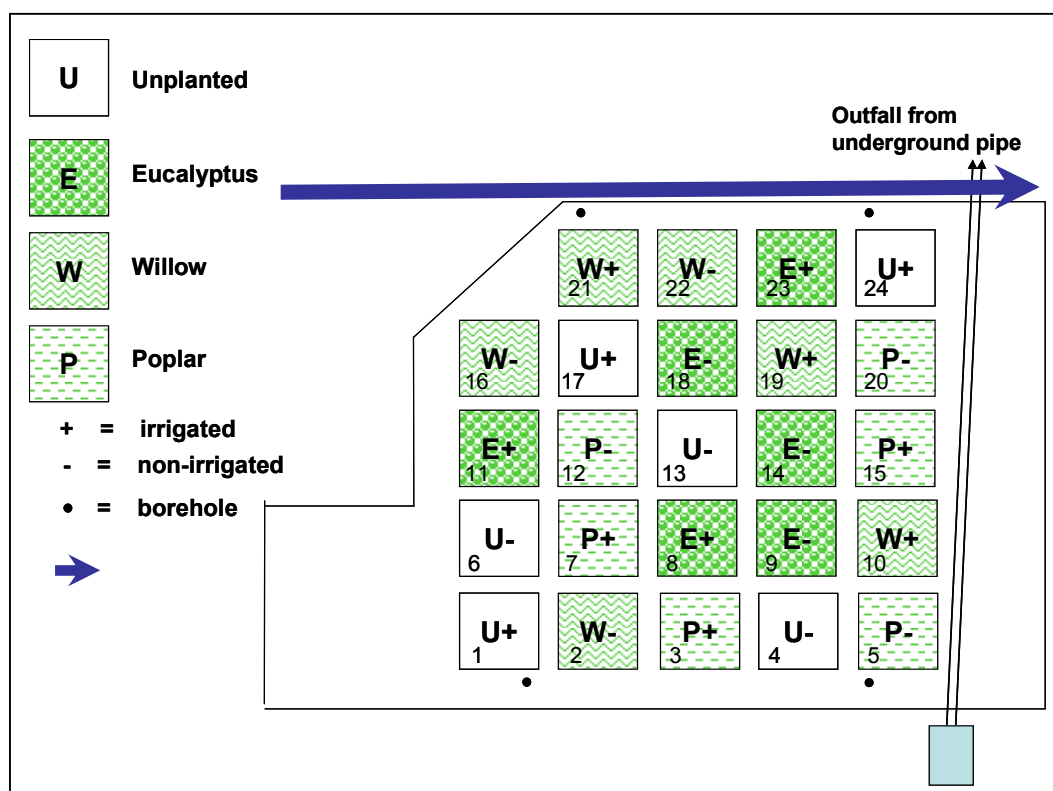


Figure 1 Cranfield site field trial map, localisation of 24 randomly distributed plots, 3 replicates of 4 covers, unplanted, eucalyptus, willow and poplar, irrigated or not.

2.3 EFFLUENT

Effluent samples were collected fortnightly, and throughout the year.

The effluent used for irrigation was a secondary treated effluent from the Cranfield University sewage treatment works (STW). This effluent meets UK regulations in term of discharge quality. Its analysis according to FAO 29 (1985) classifies its use restriction for irrigation as none to slight.

The STW has a design capacity of 2,000 p.e¹ and effluent was collected directly from the final discharge tank. Samples of effluent were collected directly from the discharge tank and analysed without filtration.

All samples were stored at 5°C and analysed within 10 days of collection.

2.4 CHEMICAL ANALYSIS OF IRRIGATION WATER

Ammonium concentrations (NH₄) were determined by the Bertholet reaction (Burkard scientific). Phosphate (PO₄) and total phosphorus (TP) concentrations were determined by the molybdate/ascorbic acid method (Burkard scientific). Total oxidised nitrogen (TON) and total nitrogen (TN) were determined by forming a red azo dye that may be measured at 520nm (Burkard scientific). Potassium, K, concentrations were measured by a flame photometer and pH and electrical conductivity (EC) were measured by Jenway 4400 pH and conductivity meter. (cf. Chapter 3, 6.1.1)

2.5 SOIL SURVEY

Soil samples were taken in February 2006 (before plantation establishment) and in February 2007 (after one year). Cores of 50mm diameter were used for 0-1.7 m soil depth from each plot in February 2006 for 0-0.5m soil depth in February 2007 and February 2008. 10 cm, 30 cm and 50 cm soil samples were considered for comparison for each year. For February 2006 and 2007, only 8 plots were samples (one of each cover, irrigated or not) but a sample from each plot were collected for February 2008.

¹ p.e.: population equivalent "The unit of measure used to describe the size of a waste water discharge. 1 population equivalent is the biodegradable load (matter) in waste water having a 5-day biochemical oxygen demand (BOD) of 60g of oxygen per day. Population equivalent doesn't necessarily reflect the actual population of a community (or Agglomeration)".(DEFRA, 2002.)

2.6 SOIL CHEMICAL ANALYSIS

All the analysis performed on soil samples were described in RB 427 (MAFF, 1986.) if not stated otherwise. (For more details, cf. chapter 3, 6.1.2)

The analysis performed were on nutrients Olsen-P (Olsen et al., 1954.), Na and available K and Na in Ammonium Nitrate extract, Total Oxidised Nitrogen (TON) and Ammonium in Potassium chloride extract, Total Phosphorus, (TP) and Total Potassium (TK), from aqua regia acid digested samples, Total Nitrogen (TN) by Atomic Absorbance Spectrophotometry. Organic matter content was assessed by loss in ignition method. Then, to address salinisation, pH, electrical conductivity (EC) and sodium absorption ratio (SAR) were measured in saturated paste extract.

A part from TON and Ammonium analysis which were conducted on moist fresh samples, samples were air dried for a week at room temperature and ground to pass a 2 mm mesh and stored at room temperature.

2.7 STATISTICAL ANALYSIS

The significance of the possible effect of irrigation and cover type on soil chemistry was assessed using analysis of variance (ANOVA), with transformations to normalise data and equalise variance as required (McBean *et al*, 1998). The general linear model option in STATISTICA 7 (StatSoft, Inc., 2005) was used for this analysis. The significance level was set at $P < 0.05$ and comparisons between means were made with the least significant difference test (Fisher-test). The factors considered in the linear model were the factor cover with 4 levels (willow, poplar, eucalyptus and unplanted), the factor irrigation with 2 levels (YES and NO), the factor depth (of sampling soil) with 3 levels (10 cm, 30 cm and 50 cm) and the factor year with 3 levels (2006, 2007 and 2008). (Cf. Chapter 3, 7)

3. RESULTS AND DISCUSSION

3.1 IRRIGATION WATER AND AMOUNT OF NUTRIENTS APPLIED BY IRRIGATION

The amounts of nutrients applied by irrigation during each irrigation season (July 2006-February 2007 and March 2007-February 2008) were calculated from the volumes of effluent applied and the average composition of effluent of 27 samples taken bi-monthly during the whole period. In the field, irrigation, via a pump was triggered every minute when soil moisture average measured for one cover type was lower than field capacity and the number of time the pump was triggered was stored in a data logger. As irrigation was applied to each tree by drip emitters calibrated to deliver 4 L.h^{-1} , the amount of effluent applied could be calculated by multiplying the duration of irrigation by this irrigation rate, and this for each cover. The different amounts were reported in Table 1 in kg per hectare.

Table 1 Cumulative amounts of nutrients applied by irrigation during the first year from July 2006 until February 2007, and during the second year, from March 2007 until February 2008.

Period	Cover				Cover			
	<i>Willow</i>	<i>Poplar</i>	<i>Eucalyptus</i>	<i>Unplanted</i>	<i>Willow</i>	<i>Poplar</i>	<i>Eucalyptus</i>	<i>Unplanted</i>
	From July 2006 to February 2007				From March 2007 to February 2008			
K applied kg.ha^{-1}	302	203	299	184	613	512	539	157
Na applied kg.ha^{-1}	705	473	697	428	1431	1195	1258	365
TN ¹ applied kg-N.ha^{-1}	342	229	338	208	694	579	610	177
Ammonium applied kg-N.ha^{-1}	16	10	15	9	32	27	28	8
TON ² applied kg-N.ha^{-1}	283	190	280	172	575	480	505	147
TP ³ applied kg-P.ha^{-1}	47	32	46	29	95	80	84	24
Phosphate applied kg-P.ha^{-1}	46	31	46	28	94	79	83	24

TN¹: Total Nitrogen, TON²: Total Oxidised Nitrogen, TP³: Total Phosphorus. With a bulk density of 1.22g.cm^{-3} , 1ha of 60 cm depth layer correspond to 7320 tonnes of soil.

As the effluent applied to all the covers was the same, the amount of nutrient applied was directly proportional to the amount of effluent applied to each cover. The amount of Nitrogen applied will be discussed to illustrate the differences of irrigated quantities. For the period July 2006 to February 2007, two groups were identified, poplar planted plots and unplanted plots receiving less than 250 kg.ha^{-1} (229 and 208 kg.ha^{-1} respectively), and eucalyptus and willow planted plots, receiving 338 and 342 kg.ha^{-1} respectively. However, for the next period, March 2007 to February 2008, the amount

of nitrogen applied to poplar planted plots were comparable to the amount of nitrogen applied to willow and eucalyptus planted plots with 579 kg.ha^{-1} , 610 and 694 kg.ha^{-1} respectively. Unplanted plots received a significantly lower amount of N (177 kg.ha^{-1}). Hence, for the first period, poplar planted plots water use was essentially soil evaporation as the amount used was comparable to unplanted plots water use and willow and eucalyptus transpirations were already significant. For the second period, poplar transpiration became comparable to willow and eucalyptus ones, more than 3 times greater than soil evaporation only.

3.1.1 Nitrogen application

The field trial was located in a location designated as a Nitrate Vulnerable Zone (NVZ) (GB, Parliament. Joint Committee on Statutory Instruments., 2008) since 1996. Hence, the limit of nitrogen application per year was 210 kg.ha^{-1} total N per year in the first 4 years after the Action Program of NVZ and then it should drop to 170 kg.ha^{-1} for farms with all their surfaces within NVZ (DEFRA, 2002). The limit of nitrogen application for grassland in NVZ was 250 kg.ha^{-1} per year and of 210 kg.ha^{-1} per year for arable zones.

Therefore, according to Figure 2, only N amounts applied to unplanted plots were complying with NVZ rules during both irrigation seasons (208 and 177 kg.ha^{-1}) and only poplar plots for the first irrigation season (229 kg.ha^{-1}). For willow and eucalyptus planted plots, the N limit was overtaken from the first year of irrigation (342 and 338 kg.ha^{-1} respectively for 2006-2007 and 575 and 505 kg.ha^{-1} for 2007-2008). The average TN application for planted plots in 2006 was $303 \pm 64 \text{ kg-N.ha}^{-1}$ and $628 \pm 59 \text{ kg-N.ha}^{-1}$ in 2007.

Total oxidised nitrogen (TON), i.e. nitrite and nitrate together, represented 83% of the N applied (Table 1).

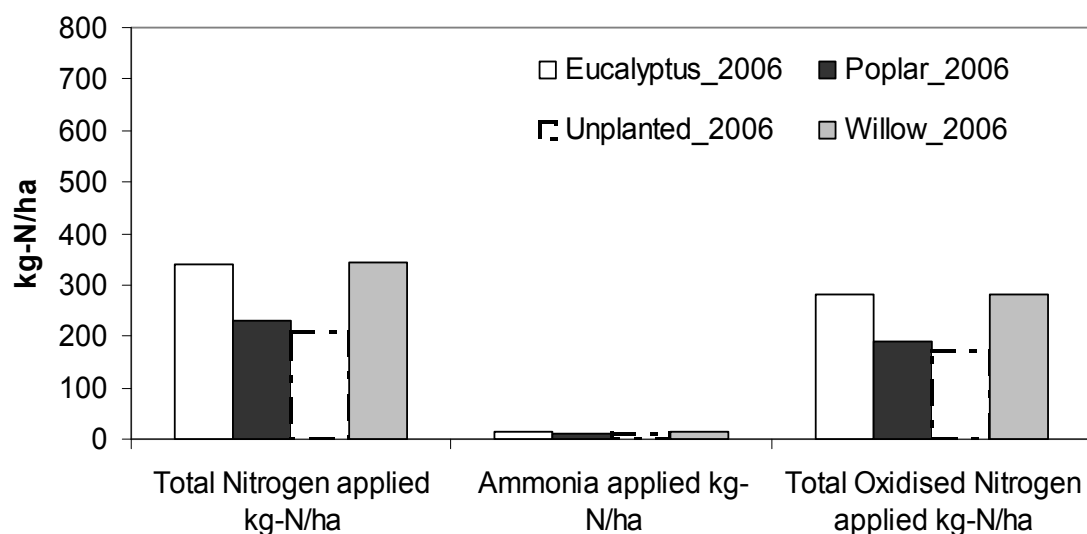
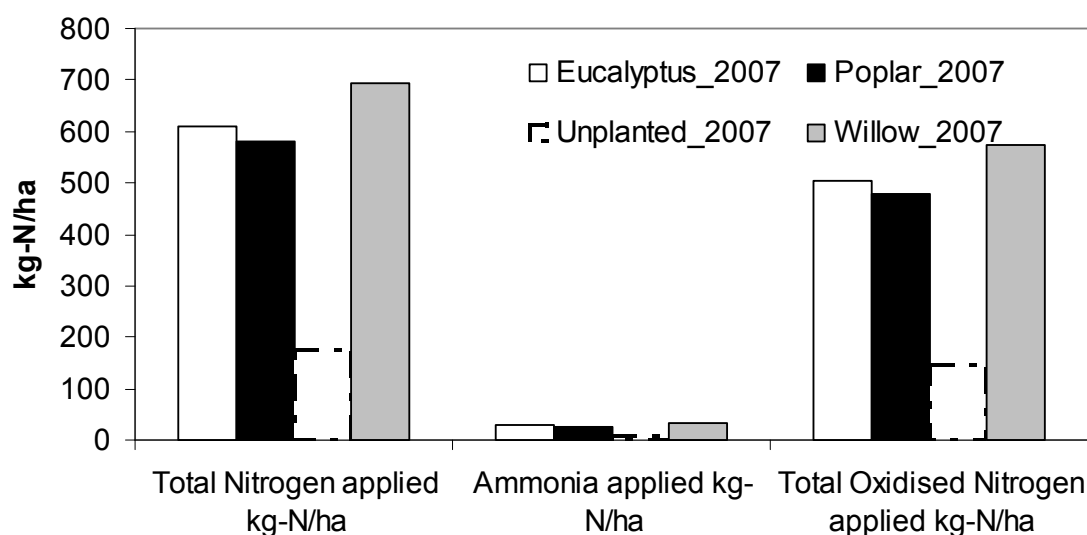
Nitrogen applied by irrigation in 2006**Nitrogen applied by irrigation in 2007**

Figure 2 Nitrogen applied by irrigation during each of the two irrigation season (July 2006-February 2007 and March 2007-February 2008) on each of the 4 covers (Eucalyptus, Poplar, Unplanted and Willow).

3.1.2 Phosphorus application

For phosphorus, there was no regulation to limit its application in the field. However, in RB209, there were recommendations for P application according to Olsen's P in soil at 15 cm depth in Appendix 4, p167 (MAFF 2000). According to the Appendix and Cranfield site Olsen's P value, the P index was 1 at the beginning of the experiment. Hence, P fertilisation could be recommended to bring P-index to 2.

According to RB 209, as there was no specific recommendation for SRC trees, guidelines for vines were considered. It was recommended to fertilise with 100 kg.ha⁻¹ of phosphate before planting for index 1.

The amounts of P applied were reported in Figure 3 in kg-P ha⁻¹. 99% of the P applied was applied as phosphate and 1 % as organic-P. Hence, as the maximum amount applied was for willow 2007 of 93 kg-P ha⁻¹, P fertilisation was less than that recommended. The average P application on planted plots for 2006 was 42±9 kg-P.ha⁻¹, 29 kg-P.ha⁻¹ for unplanted plots and for 2007 was 86±8 kg-P.ha⁻¹ for planted plots, 24 kg-K.ha⁻¹ for unplanted plots. Therefore, P applications were under the RB 209 recommendations for all plots during the whole experiment.

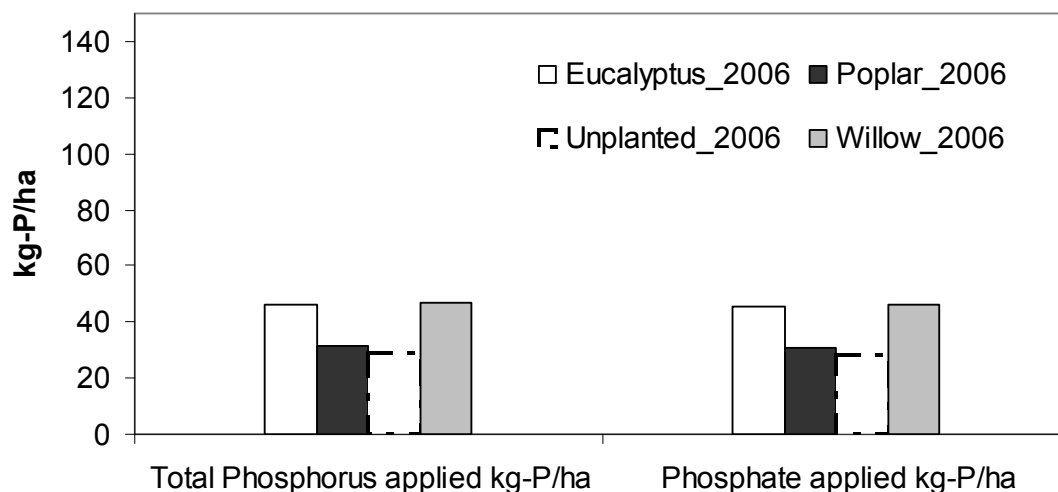
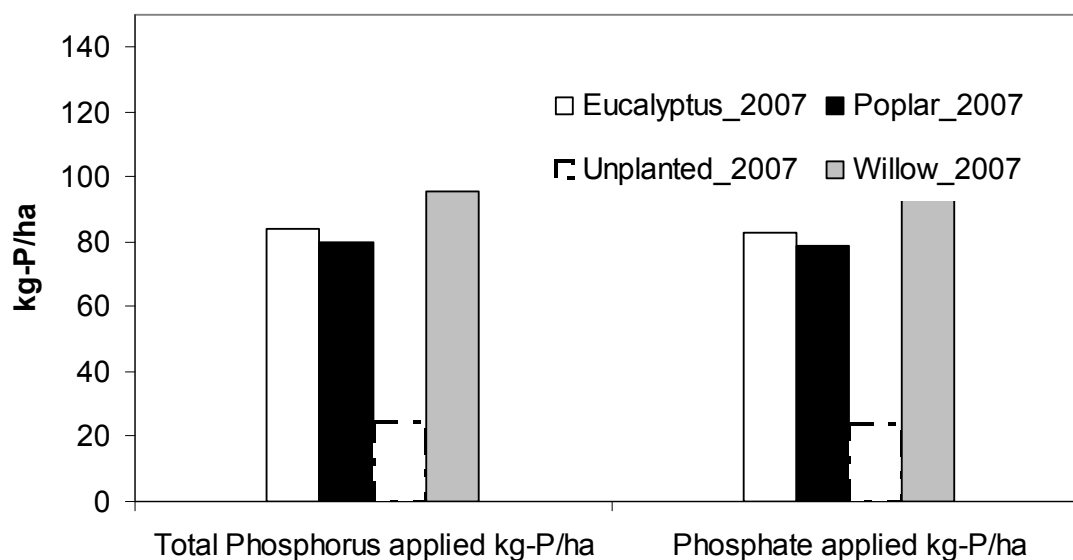
Phosphorus applied by irrigation in 2006**Phosphorus applied by irrigation in 2007**

Figure 3 Phosphorus applied by irrigation during each of the two irrigation season (July 2006-February 2007 and March 2007-February 2008) on each of the 4 covers (Eucalyptus, Poplar, Unplanted and Willow).

3.1.3 Potassium application

For K, there was no regulation to limit its application in the field. However, in RB209, there were recommendations for K application according to K in soil extracted in ammonium nitrate in Appendix 4, p167 (MAFF 2000). According to the Appendix and Cranfield site K value (222 mg-K.L^{-1}), the K index was 2 at the beginning of the experiment. Hence, K fertilisation for fruit, vines and hops recommended 50 kg.ha^{-1} of potash (K_2O) before planting p122 (MAFF 2000).

The amounts of K applied were reported in Figure 4 in kg-K.ha^{-1} . The average K application on planted plots for 2006 was $268 \pm 56 \text{ kg-K.ha}^{-1}$, 184 kg-K.ha^{-1} for unplanted plots and for 2007 was $555 \pm 52 \text{ kg-K.ha}^{-1}$ for planted plots, 157 kg-K.ha^{-1} for unplanted plots. Therefore, K applications were over the RB 209 recommendations for all plots during the whole experiment.

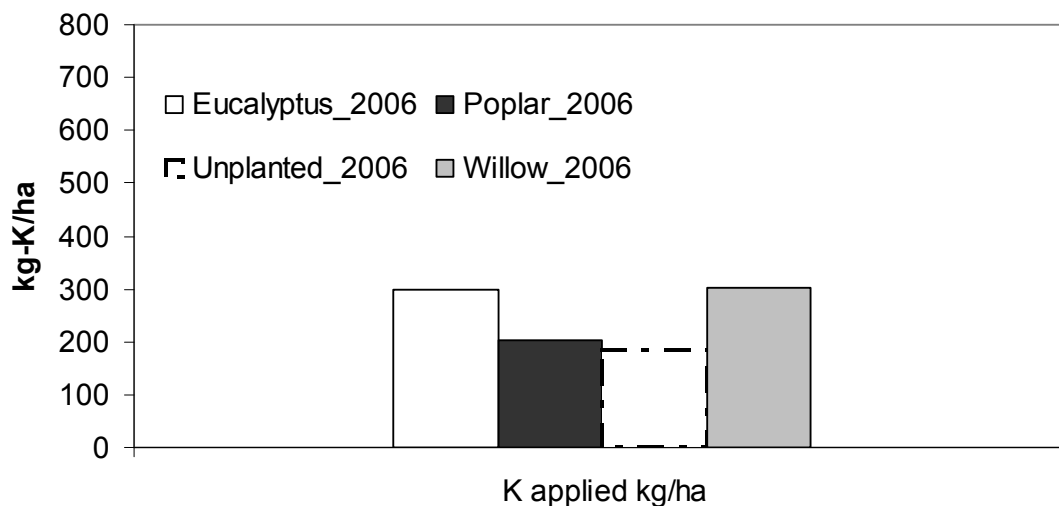
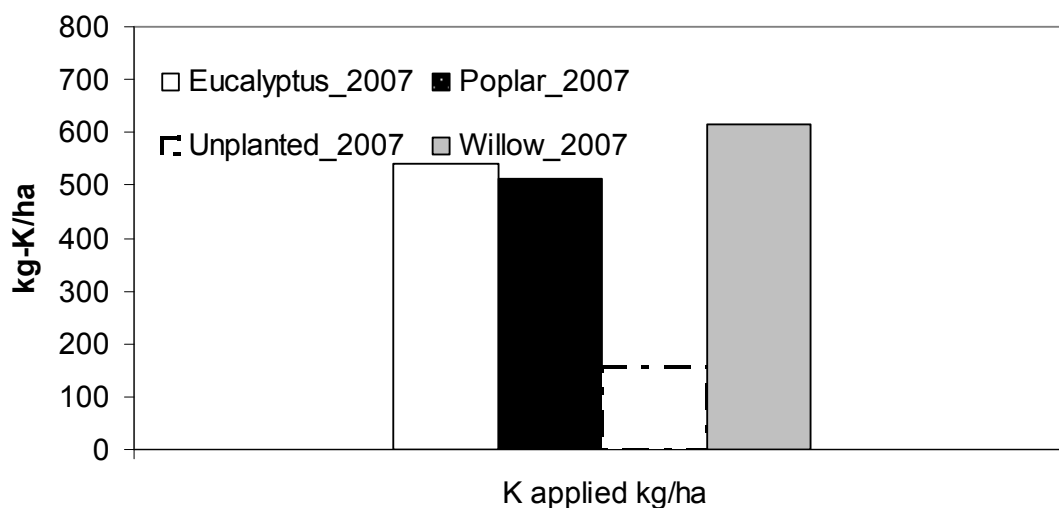
Potassium applied by irrigation in 2006**Potassium applied by irrigation in 2007**

Figure 4 Potassium applied by irrigation during each of the two irrigation season (July 2006-February 2007 and March 2007-February 2008) on each of the 4 covers (Eucalyptus, Poplar, Unplanted and Willow). $50 \text{ kg} \cdot \text{ha}^{-1}$ of K recommended by RB 209.

3.1.4 Nutrients application

Average wastewater composition was comparable to nutrient proportions needed by SRC trees to grow (Aronsson and Perttu, 2001). (Chapter 2, 2.1.2)

Table 2 Comparison of the relative concentrations of N, P, K in the different municipal wastes, optimum composition for SRWC, Eucalyptus and Poplar nutrients uptake in relation to N=100, adapted from (Aronsson and Perttu, 2001).

<i>Element</i>	<i>Untreated wastewater</i>	<i>Tertiary treated wastewater</i>	<i>Cranfield secondary treated effluent</i>	<i>Optimum composition for SRWC</i>	<i>Eucalyptus urophylla hybrids (Brazil 7yrs)</i>	<i>Populus trichocarpa</i>
N	100	100	TN: 100	100	100	100
P	17.5	≈4.5	TP: 15 (1/5 of optimum composition for SRWC ²)	14	8	15
K	64	≈60	K: 160 (11 times of optimum composition for SRWC)	72	57	45

P proportion in Cranfield secondary treated effluent was 1/5 lower than in the proportion optimum composition for SRWC and K proportion was 11 times higher than in the proportion optimum composition for SRWC (Table 2). Therefore, N applications were over the NVZ recommendations for all plots during the whole experiment. P applications were under the RB209 recommendations for all plots during the whole experiment. K applications were over the RB209 recommendations for all plots during the whole experiment.

3.2 SALINITY

3.2.1 Effluent pH, EC and Na concentration

When the water used for irrigation contains a high concentration of dissolved salts, it can damage the soil. These salts can accumulate and provoke damage on soil physical properties. Clay particles flocculation and clay swelling induce loss of soil structure and decrease hydraulic conductivity (Rowell, 1994) (Sumner, 1993). Therefore, FAO 29 (Westcot et al., 1985.), was taken as a reference to assess any risk for salinisation by irrigation with secondary treated effluent. Moreover, average pH, electrical conductivity (EC) and Na concentration were measured bi-monthly from July 2006 to February 2008 are compared to FAO 29 guidelines values (Table 3).

² SRWC: short rotation willow coppice

Table 3 Secondary treated effluent average electrical conductivity, pH and sodium concentration on N=27 samples collected bi-monthly from July 2006 until February 2008. (N, number of samples)

	pH	EC (dS.m ⁻¹)	Na (mg.L ⁻¹)	Na (me.L ⁻¹)
Average	7.3	0.7	63.2	2.75
Standard deviation	0.5	0.1	41.7	1.81

pH was in normal range (7.3 in the normal range defined as 6.5-8.4), EC was at the limit between no restriction to slight to moderate restriction and the mean Na concentration of 63.2±41.7 mg.L⁻¹ placed this effluent as use with restriction for sensitive crops. However, willow, poplar and eucalyptus were not sensitive crops to sodium. In 2007, more than a tonne of Na was applied to plots planted with eucalyptus, willow and poplar (Figure 5).

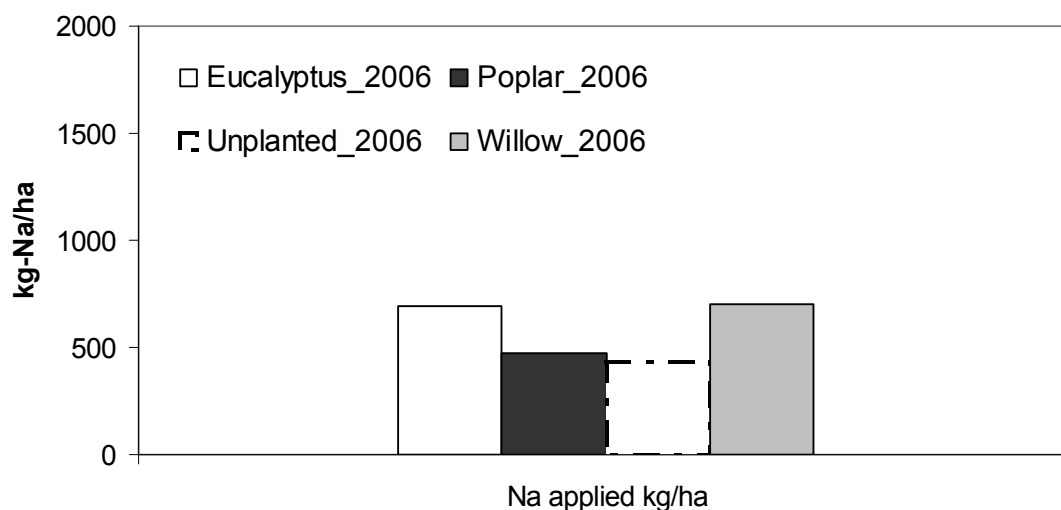
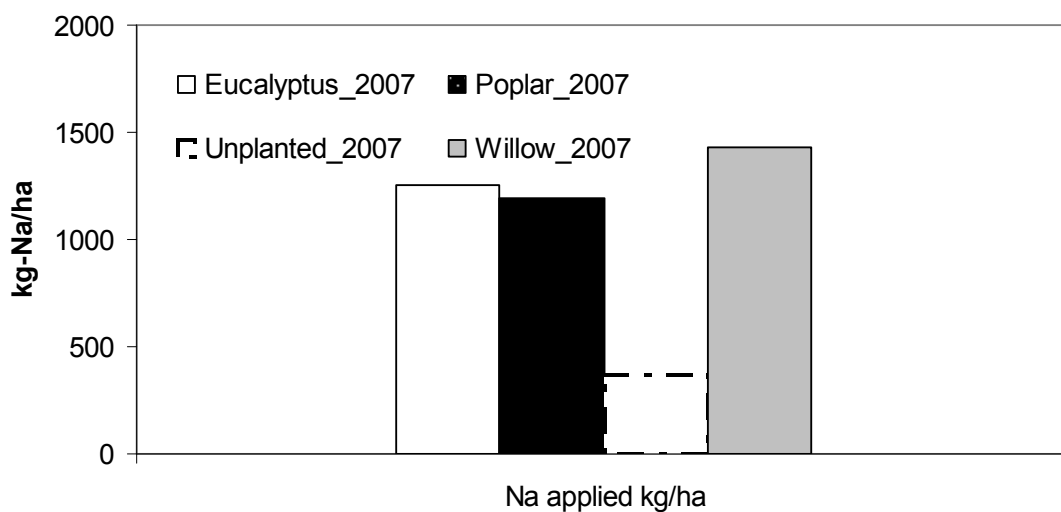
Sodium applied by irrigation in 2006**Sodium applied by irrigation in 2007**

Figure 5 Sodium applied by irrigation during each of the two irrigation season (July 2006-February 2007 and March 2007-February 2008) on each of the 4 covers (Eucalyptus, Poplar, Unplanted and Willow).

3.2.2 Sodium Adsorption Ratio (SAR, qualitative) in irrigation effluent

To assess the specific effect of sodium salts, and their potential accumulation in soil, different parameters can be considered; SAR or sodium adsorption ratio and ESP or exchangeable sodium percentage (Richards and Allison, 1954.).

SAR was defined as the proportion of sodium cations compared to calcium and magnesium cations.

$$SAR = \frac{[Na^+]}{\left[\frac{Ca^{2+} + Mg^{2+}}{2} \right]^{1/2}} \quad \text{Equation 1 (Richards and Allison, 1954.)}$$

Hence, it involves measurements of calcium and magnesium concentrations (Richards and Allison, 1954.) in the solution (irrigation water as in (Westcot et al., 1985.) or soil saturated paste extract). And it has not been measured over the whole period but only on one sample on the 22/07/08. This unique SAR measurement was used only to give an idea on the salinity of the effluent used for irrigation.

ESP was defined as the “amount of exchangeable sodium expressed as a percentage of the cation exchange capacity (CEC³)” (Rowell, 1994). According to Richards (Richards and Allison, 1954.) SAR and ESP values can be linked by Equation 2:

$$ESP = \frac{100 * (0.01475SAR - 0.0126)}{1 + (0.01475SAR - 0.0126)} \quad \text{Equation 2}$$

There was only one measure of SAR and ESP in effluent and it was 1.9 and ESP of 1.6 with EC=0.6 dS.m⁻¹ (the mean value was of 0.7±0.1 dS.m⁻¹).

According to Richards and Allison (1954), the combination of ESP and EC places this sample as neither saline nor alkali as EC<4 dS.m⁻¹ and ESP<15.

According to FAO 29 (Westcot et al., 1985.), the EC, sodium concentrations and SAR combination places this effluent at the border between no salinity risk, no infiltration risk and slight to moderate risk category. Moreover, according to (Sumner, 1993) below an ESP of 15 %, little clay swelling was expected to occur, below 15 %, no sodicity related problems should be expected.

³ Cation exchange capacity or CEC: the proportion of cations “held by electrostatic forces on soil particle surfaces to balance the surface negative charge” (Rowell, 1994)

3.3 SOIL PH

According to (MAFF, 1986), for a heavy soil (clay loams and clays), the recommended pH was of 6.5 and the target pH of 6.7. However, soil in Cranfield was a calcareous clay (NSRI, 2008), therefore, alkaline pH (>7) can be expected (Rowell, 1994).

At the beginning of the experiment, average soil pH was 7.6; i.e. in the category slightly alkaline and could induce a deficiency in Mn and Br as their availabilities were reduced for alkaline pH (FAO, 1985). Slight chlorosis of leaves was observed on poplar and willow trees due probably to Mn deficiency (Behboudian et al., 2003).

Statistically, soil pH became significantly more alkaline between 2006 and 2007 and then became significantly less alkaline, indeed neutral between 2007 and 2008 (Figure 6). However, from a pH value point of view, these variations were not important as soil remained slightly alkaline during the whole experiment.

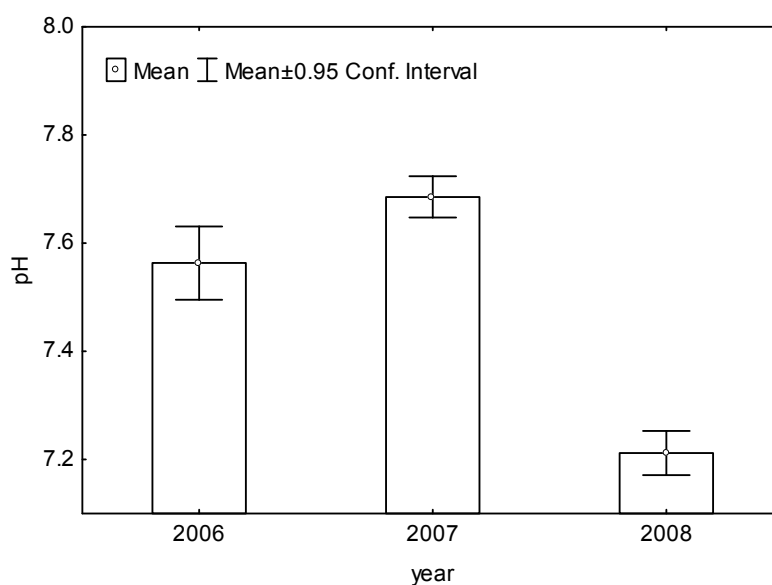


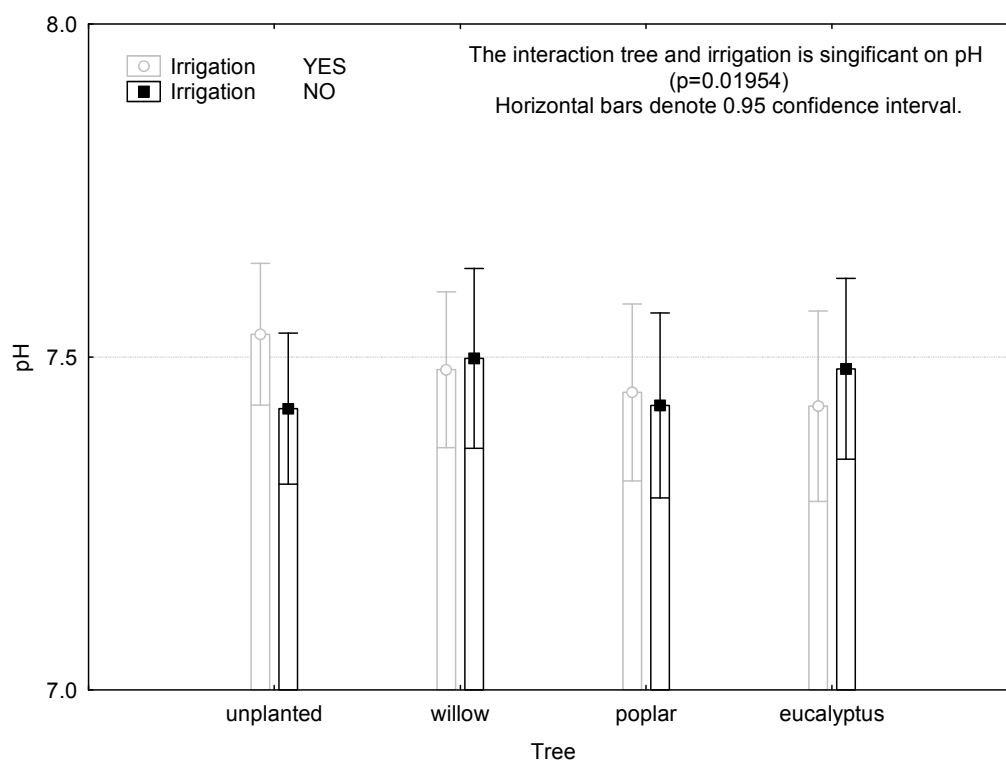
Figure 6 Average pH per year. Vertical bars denote 0.95 confidence interval. Soil pH above 7 are considered alkaline (Rowell, 1994).

To identify possible significant effect of the different covers, irrigation, depth of sampling and date on soil pH, ANOVA described in Chapter 3, section 7, was conducted on pH measured on homogenised samples of soil. (Table 4)

Table 4 ANOVA table for pH of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008. (significant factors in bold)

	Degree. of Freedom	pH - F -	pH - p -
Intercept	1	293561.0	0.00
year(Cover*Irrigation*Depth)	48	8.0	0.00
Cover	3	1.4	0.24
Irrigation	1	0.5	0.48
Depth(Cover*Irrigation)	16	1.0	0.51
Cover*Irrigation	3	3.5	0.02
Error	96		
Total	167		

Also, the acidification between 2007 (pH=7.7) and 2008 (pH=7.2) was expected. Indeed, leaves were left on the soil surface only during autumn 2007 to decompose in place and contributed to the development of organic matter for planted plots. The added organic matter would tend to decrease soil pH (Nutrient Manager, 1996). Although Na was applied on soil surface by irrigation and effluent pH was 7.3 ± 0.5 in average over the duration of the experiment, the water condition of soil (maintained to field capacity) might explain less neutralisation of soil pH on irrigated plots.

**Figure 7 Effect of cover type and irrigation on pH data presented for averages of 3 depths. Vertical bars denote standard deviation.**

Only the cultivation of irrigated eucalyptus neutralised soil pH significantly. However, the natural evolution of soil with presumably development of organic matter in soil was also neutralising significantly soil pH. Other processes might also have lead to this acidification: increased organic matter in soil, oxidation of ammonium ions brought by fertigation, loss of nitrate in drainage water or export of alkalinity of organic ions as observed on Australian soils (Lockwood et al., July 2004). The changes in SAR will be commented on as well. Moreover, the development of organic matter will be assessed on observing the evolution of TN, TP and TK.

3.4 SOIL SAR, SODIUM, CALCIUM+MAGNESIUM IN SATURATED PASTE EXTRACT

Salinisation can be assessed by SAR value observed jointly with EC value. For this reason, first the evolution of SAR was looked at. As SAR was defined by Na and Ca+Mg concentrations ratio (Equation 1, 3.2.2), therefore, any changes in SAR would be the results of either Na or Ca+Mg concentrations changes or only Na or Ca+Mg concentration changes. SAR, Na (mg.L^{-1}) and Ca+Mg (mg.L^{-1}) were measured from saturated paste extract.

These data had to be transformed (log) to ensure residuals normal distribution.

Table 5 ANOVA table for log(SAR), log(Na), log(Ca+Mg) of soil samples taken on each plot in February 2006, 2007 and 2008. (Significant factors in bold)

	Degree. of Freedom	log(SAR) -F-	log(SAR) - p -	log(Na) F	log(Na) - p -	log(Ca+Mg) F	log(Ca+Mg) p
Intercept	1	1838.8	0.000	25.99	0.000	1263.19	0.000
Year(Cover*irrigation)	16	66.7	0.000	82.03	0.000	1.45	0.182
Cover	3	0.18	0.913	0.16	0.925	0.07	0.976
irrigation	1	11.90	0.002	7.33	0.011	0.04	0.852
Cover*irrigation	3	0.23	0.879	0.21	0.886	0.61	0.613
Error	32						
Total	55						

According to the ANOVA table (Table 5), irrigation and year factors had a significant effect on SAR and Na evolution by increasing them significantly.

Irrigated plots average SAR regrouped on the 3 years and 4 covers was significantly higher than on non-irrigated plots. Hence, according to SAR definition (Richards and Allison, 1954.), the application of Na by effluent onto soil significantly increased Na proportion compared to Ca and Mg in soil. (Table 5, Figure 8). Therefore, an increase in Na due to irrigation, significantly increased SAR. Irrigation has significantly increased soil SAR in 2008 under willow and eucalyptus planted plots. Indeed those plots received 1431 kg/ha and 1258 kg/ha of Na respectively compared to 1195 kg/ha and 365 kg/ha for poplar and unplanted plots (Figure 5, 3.2.1).

Soil capacity to adsorb ions depends on its cation exchange capacity (CEC). Cations are adsorbed in exchange of a group of cations already on the exchange complex. These cations on the complex are commonly Al^{3+} , Ca^{2+} , Mg^{2+} , K^{+} and H^{+} (Rowell, 1994).

Therefore, when Na^+ was added, in order to be fixed in the soil matrix on the negative surface of the clay by electrostatic forces, other cations had been exchanged. As Cranfield soil was a calcareous clay, it was unlikely to find Al^{3+} as they are principally present in acid soil and low H^+ and not in an alkaline (section 3.3) (Rowell, 1994). The exchangeability order of the common cations in calcareous soil is: Na^+ lost first, then Ca^{2+} , then Al^{3+} and finally K^+ .

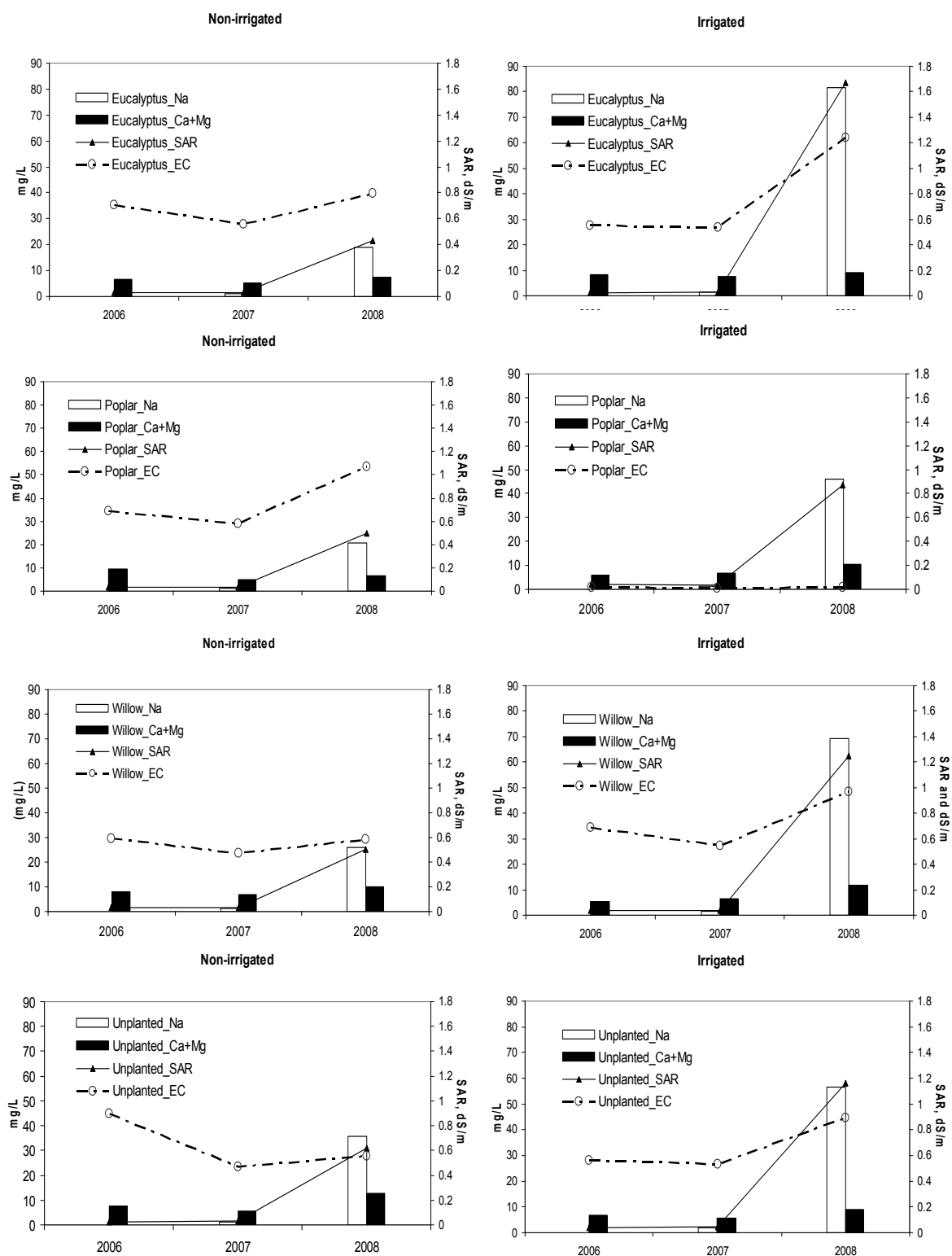


Figure 8 Evolution of Na, Ca+Mg concentrations (mg.L^{-1}) and SAR and EC (dS.m^{-1}) for 2006, 2007 and 2008 under 4 covers irrigated or not. (for clarity 0.95 confidence intervals were not represented on these graphs)

The year factor was also significantly affecting SAR. The increase in SAR, i.e. the increase of Na compared to Ca and Mg, was progressive as soil SAR increased significantly from 2006 to 2007 (1.08 time, not significant) and then from 2007 to 2008 (27.5 times). The increase was greater after the second year of irrigation (Figure 9)

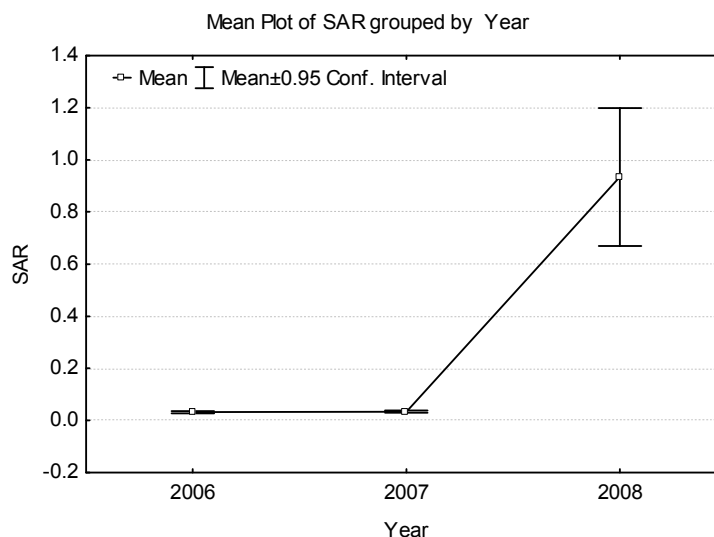


Figure 9 mean SAR regrouped by irrigation or not. Vertical bars denote standard deviation.

As SAR was defined as the ratio of Na concentration on the square root of (Ca+Mg) concentration, the increase of SAR could be the result either of a significant increase of Na or a significant decrease of (Ca+Mg). The latter could have been possible as it would have resulted in a significant acidification of pH in soil, which was observed and commented on in the previous paragraph, however, it did not happen (Figure 7) and Ca+Mg concentrations remained comparable from year to year. ANOVA concluded Na increased significantly over the years (Figure 8) and more under irrigated plots but (Ca+Mg) did not change significantly during the same period and under the same conditions. (Figure 8). In effect, great amounts of Na were applied each year ($> 500 \text{ kg-Na.ha}^{-1}$ for the first year and $> 1,200 \text{ kg-Na.ha}^{-1}$ for planted plots, cf. Figure 5, Section 3.2.1)

3.5 ESP AND EC

ESP and EC were compared jointly to assess alkalinity or sodicity of a soil or water. (Richards and Allison, 1954.). There were 4 categories (Figure 10):

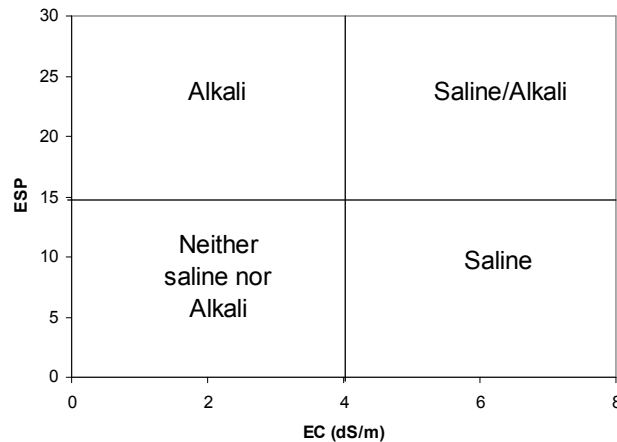


Figure 10 Soil classification according to EC and ESP. (Richards, 1954)

ESP and SAR were (Richards and Allison, 1954.) linked by Equation 1:

$$ESP = \frac{100 * (0.01475SAR - 0.0126)}{1 + (0.01475SAR - 0.0126)} \quad \text{Equation 3}$$

Alkali, saline and saline/alkaline soils definitions and management were summarised from definition given in (Richards and Allison, 1954.):

- Saline/alkali soil: for soil which $ESP > 15$ and $EC > 4 \text{ dS.m}^{-1}$ and $pH \geq 8.5$. This type of soil results of a combination of processes of both salinisation and alkali-sation. Soil presents both high Na content and exchangeability and also particles remained flocculated because of the high pH. For these soils, leaching soluble salts won't recover soil quality until soil favourable physical conditions were not restored.
- Non alkaline-Saline soil: for soil which $ESP < 15$ and $EC > 4 \text{ dS.m}^{-1}$ and $pH \leq 8.5$. Saline soil contains high concentration of readily soluble salts and low solubility salts (gypsum, lime). Salts need to be leached and soil can be recovered and become normal.

- Non saline-Alkali soil: for soil which $ESP > 15$ and $EC < 4 \text{ dS.m}^{-1}$ with $8.5 < pH < 10.5$. After leaching a saline/alkaline soil with its soluble salts, and no gypsum added to regulate Na exchange, the resulting soil was a non saline-alkaline soil.

And according to ESP and EC, all the samples for the 3 years were classified as neither saline nor alkali.

EC (dS.m^{-1}) data measured on saturated paste extract had to be transformed (log) to ensure residuals normal distribution. But ANOVA revealed none of the factors had a significant effect on EC (Table 6). Hence, even though SAR increased significantly, it didn't affect EC in soil saturated paste extract.

Table 6 ANOVA table for log(EC) of saturated paste extract from soil samples taken on each plot in February 2006, 2007 and 2008. (Significant factors in bold)

	Degree. of Freedom	log(EC) - F -	log(EC) - p -
Intercept	1	80.74	0.000
Year(Cover*irrigation)	16	1.60	0.127
Cover	3	0.22	0.881
irrigation	1	0.23	0.636
Cover*irrigation	3	0.55	0.649
Error	32		
Total	55		

As a significant increase was observed for SAR, it was necessary to know if this increase was problematic or not and if it was impairing soil quality.

There was a significant increase of SAR in soil during both years of irrigation, however, there was no significant salinisation of the soil.

But EC did not change significantly and the increase of ESP because of SAR did not result in a real alkalisation¹ of soil (Table 6). Alkalinity of soil was a concomitant problem with sodic soil as high Na concentrations in soil increase soil pH significantly (Szabolcs, 1989). However, on all plots, SAR increased progressively, for both categories, irrigated or not. (Figure 8) Hence, irrigation alone can't explain this slight alkalisation.

¹ (Szabolcs, 1989) "Alkali soils: soils affected by sodium salts capable of alkaline hydrolysis (mainly NaHCO_3 , Na_2CO_3 and Na_2SiO_3)"

3.6 SOIL NA EXTRACTED IN AMMONIUM NITRATE OR EXTRACTABLE NA

Na content in soil can be determined in soil saturated paste (section 3.5) or by ammonium nitrate extraction. The latter corresponds to extractable Na in soil. As for saturated paste methodology, the amount of water necessary to make the saturated paste is not usually recorded and was not recorded for 2006 and 2007 measurements. Therefore, Na from saturated paste could not be related to a mass of dry soil and for this reason, to assess Na concentrations evolution per kg of soil, extractable Na were measured and analysed.

ANOVA performed on Na concentration in soil extracted in ammonium nitrate revealed all factors (cover, irrigation, interaction of cover and irrigation, depth and time) have a significant effect. (Table 8)

Table 7 ANOVA table for Na of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008. (significant factors in bold)

	Degree. Of - Freedom	Na mg/kg F	Na mg/kg p
Intercept	1	6914.90	0.000
year(Depth*Cover*Irrigation)	48	6.81	0.000
Depth(Cover*Irrigation)	16	3.00	0.000
Cover	3	6.86	0.000
Irrigation	1	100.95	0.000
Cover*Irrigation	3	9.87	0.000
Error	140		
Total	211		

The LSD table of the factor interaction between cover and irrigation showed that there was an irrigation effect only on planted plots and there was a cover effect only on irrigated plots. In other words, Na accumulated significantly under irrigated plots and accumulated even more where trees were planted (Figure 11).

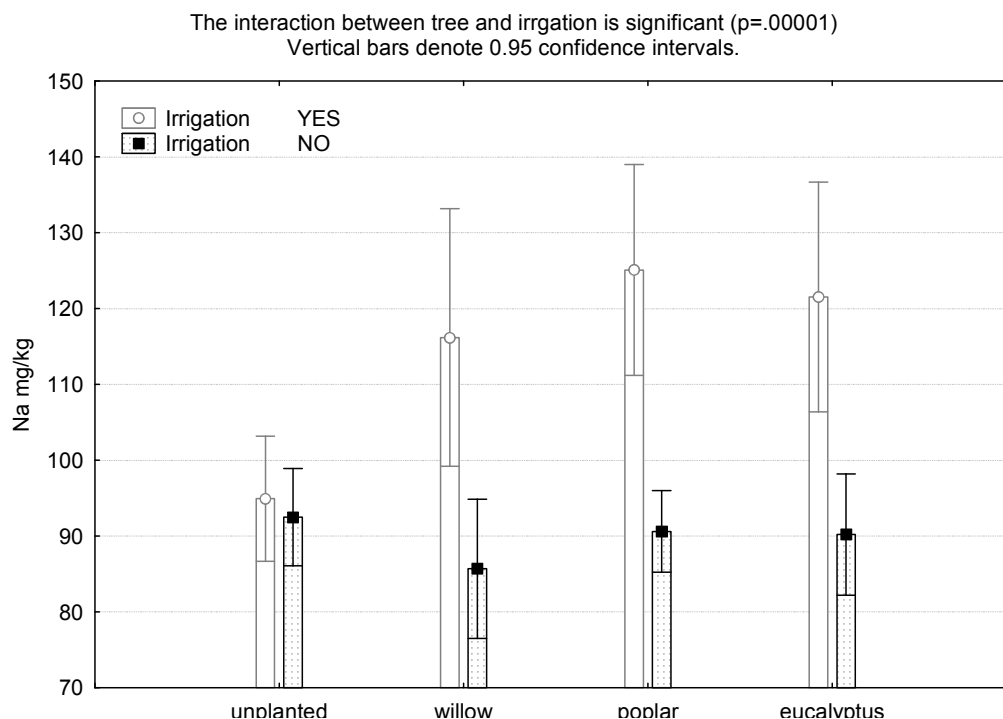
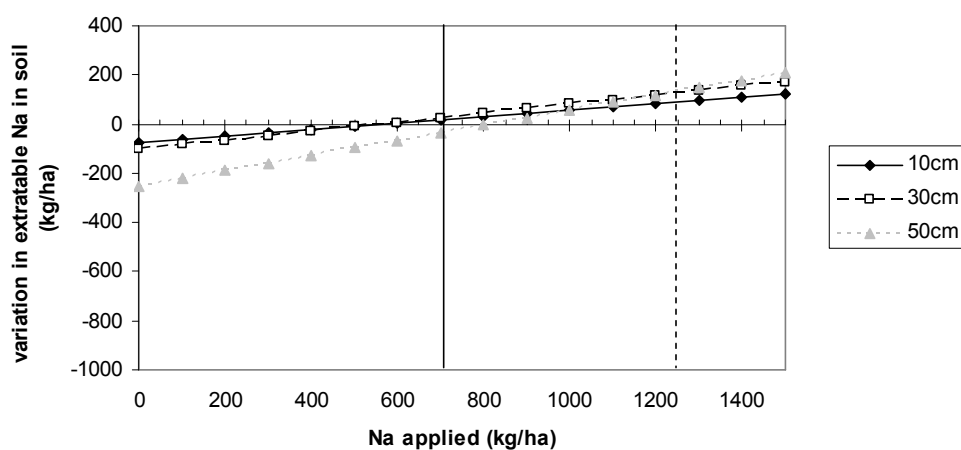
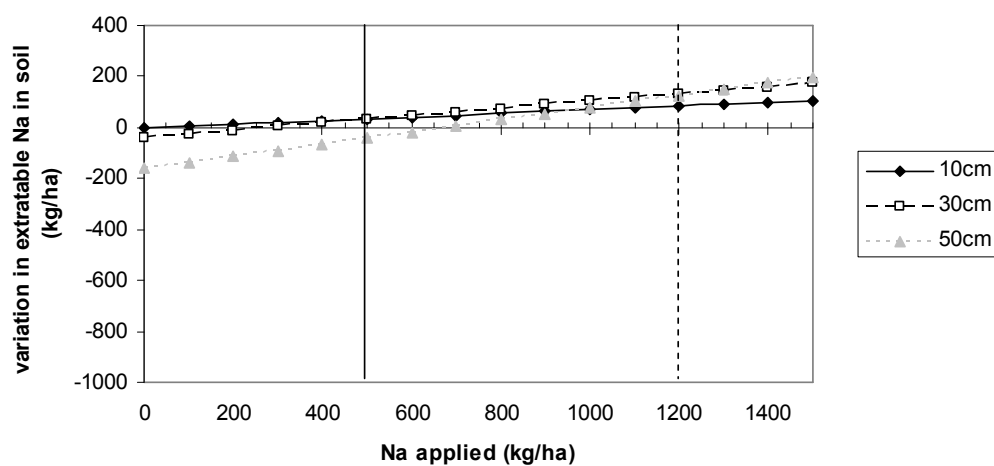
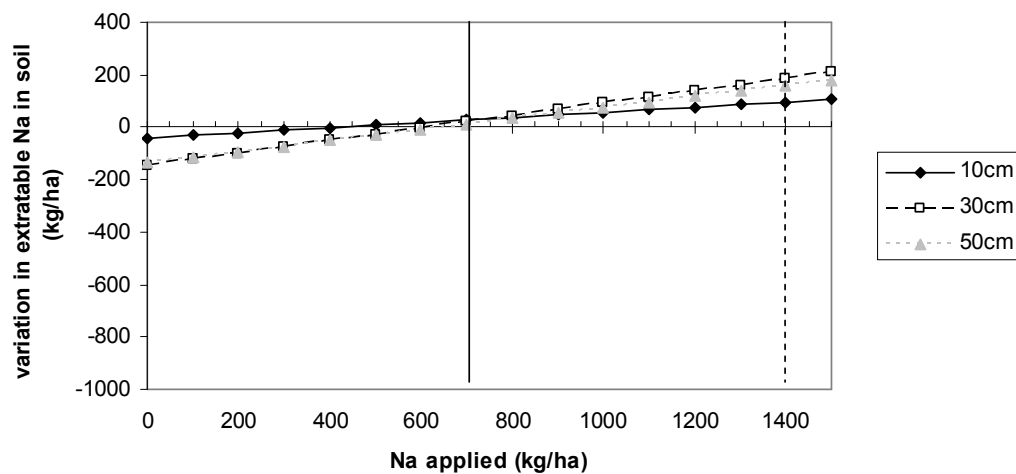


Figure 11 Average extractable Na concentration in soil grouped by covers from samples collected at 3 depth (10 cm, 30 cm, 50 cm) and 3 years (2006, 2007, 2008).

The relevance of the relationship between applied Na and subsequent variation of extractable Na in soil is low. This is because all the plots with the same covers received the same amount of effluent and there were only 2 values for each cover to calculate linear regression. Then for each cover, the established linear regressions were plotted in Figure 12 for applied Na ranging from 0 to 1500 kg.ha⁻¹ in abscise and the corresponding variation in extractable Na in soil. For eucalyptus and poplar planted plots, extractable Na accumulated more in depth because of sloping. This represents the accumulation of extractable Na if positive, subsequent to Na application with effluent, are greater with depth. For willow planted plots, it was not as clear as for eucalyptus and poplar planted plots for 30 and 50 cm depth. For unplanted plots, there was no extractable Na accumulation in the different layers of soil subsequent to Na application if over 500 kg.ha⁻¹ but extractable Na leaching and loss from soil (slopes were negative for all depths, Figure 12²). Therefore, the more Na applied over 500 kg.ha⁻¹, the more water was applied as well as part of fertigation. In spite of the

automated irrigation system set to maintain soil moisture to field capacity (Chapter 3, 5.1), extractable Na evolution suggests there was drainage occurring as the most effluent received, the more extractable Na was leached.

² As there were only 2 points to calculate the different linear regressions, the trends are considered but values might be only indicative.

Eucalyptus**Poplar****Willow**

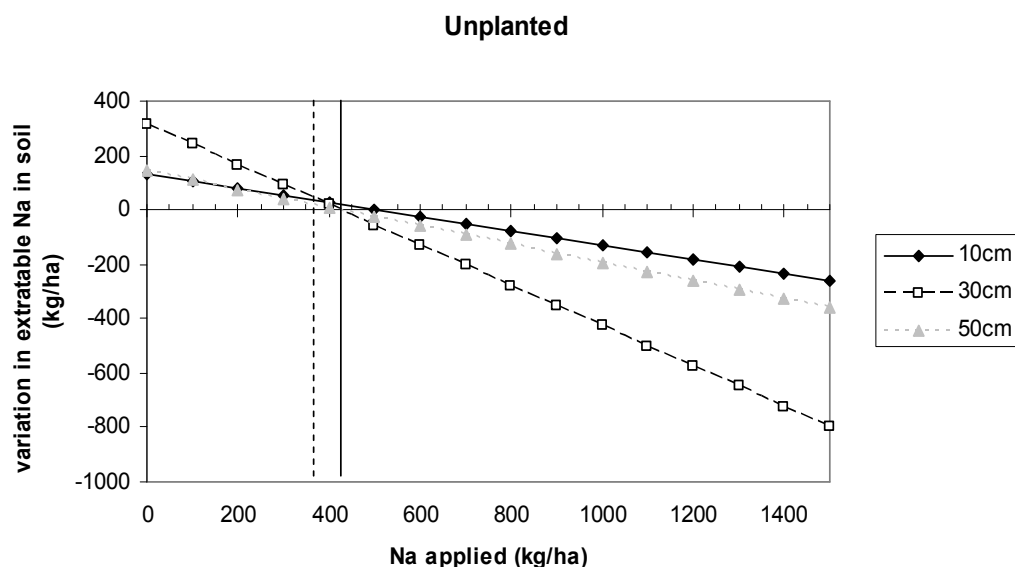


Figure 12 Linear regression on variation in extractable Na in soil (kg/ha) at 10, 30 and 50 cm in relation with the Na amount applied (kg/ha). Straight vertical line represents the amount of Na applied in 2006 and dotted vertical line represents the amount of Na applied in 2007.

Thus, the increase of extractable Na in irrigated plots was greater at 10 cm and 30 cm than at 50 cm with a significant increase for unplanted and willow plots (cf. slopes at 10 and 30 cm were steeper than at 50 cm, Figure 12). Hence, Na applied by irrigation did significantly accumulate at 10 cm for unplanted plots and willow planted plots. But, Na was distributed in the lower layers under poplar and eucalyptus because slopes at 30 and 50 cm were steeper than at 10 cm depth (Figure 12). And also because there was a significant effect of irrigation at all depths, under all covers as it was reported in Table 7 and Figure 13.

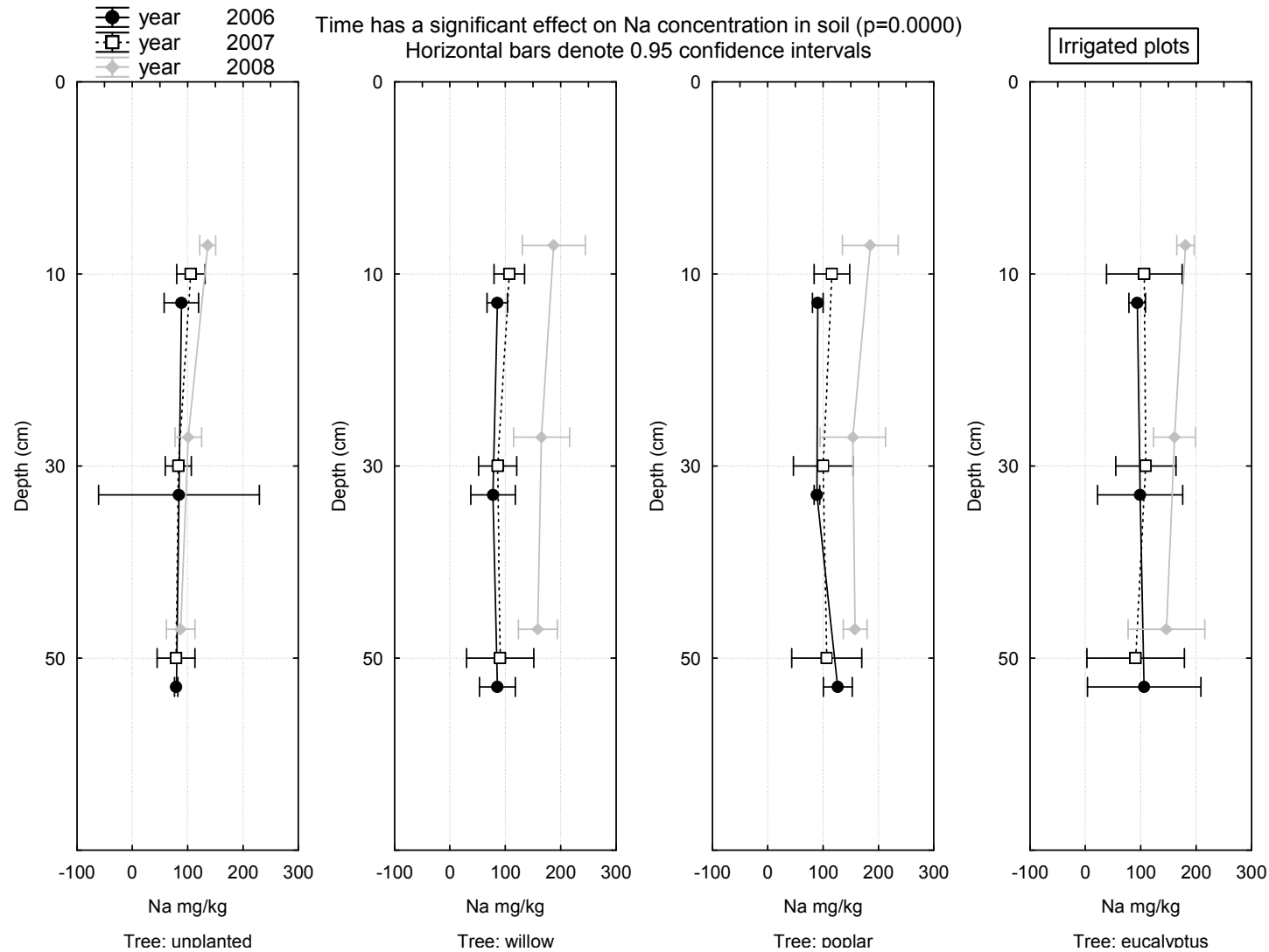


Figure 13 Evolution of extractable Na concentration in soil samples collected at 3 depths (10 cm, 30 cm and 50 cm) under 4 covers (unplanted, willow, eucalyptus, poplar) from irrigated plots. Horizontal bars denote 0.95 confidence interval. The graph is drawn staggered at each depth for clarity but all the measurements were performed at the same depths.

Irrigation effect was significant from 2007 the first year of irrigation (extractable $\text{Na}_{\text{irrigated}} = 1.16 * \text{Na}_{\text{non-irrigated}}$) but very much more pronounced after the second year of irrigation (extractable $\text{Na}_{\text{irrigated}} = 1.64 * \text{Na}_{\text{non-irrigated}}$).

The increase of Na in soil occurred on irrigated planted plots (Figure 13).

The greatest increase was on poplar plots (extractable $\text{Na}_{\text{irrigated}} = 1.36 * \text{Na}_{\text{non-irrigated}}$), however, the increase for the other trees were from the same range (willow, $\text{Na}_{\text{irrigated}} = 1.36 * \text{Na}_{\text{non-irrigated}}$; eucalyptus, $\text{Na}_{\text{irrigated}} = 1.35 * \text{Na}_{\text{non-irrigated}}$).

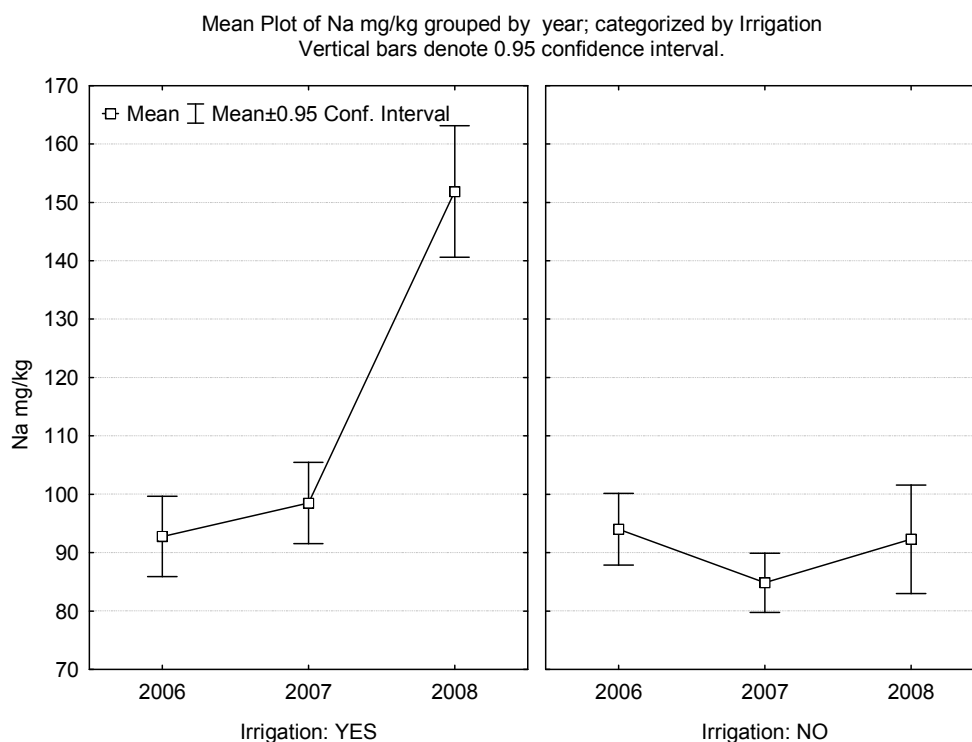


Figure 14 Extractable Na concentration in soil grouped by year and irrigation. Vertical bars denote 0.95 confidence interval.

The irrigated amount on planted trees significantly increased Na concentration in soil from the first year of irrigation with a greater effect on the second year. The average amount of Na applied in 2006 was $315 \text{ kg} \cdot \text{ha}^{-1}$ and $580 \text{ kg} \cdot \text{ha}^{-1}$ in 2007. These amounts corresponded to over 340 % of average extractable Na in 2006 and over 580 % of extractable Na in 2007. Therefore, the significant effect of Na application on soil extractable Na was expected.

This is in accordance with the SAR and pH results as an increase of Na in soil contributes to an acidification of the soil. There is a progressive acidification and salinisation of soil, significant on irrigated plots after two years of irrigation, however, noticeable also on non-irrigated plots. Hence, this is the consequence of the combination of very wet conditions on very heavy clay. However, under non-irrigated conditions, even though SAR, ESP and pH increased significantly, Na concentration in soil didn't. This is showing that any cultivation or treatment of this type of site would lead to salinisation of soil with a potential risk of acidification if not monitored.

3.7 SOIL ORGANIC MATTER CONTENT

(Rowell, 1994) defined soil organic matter (SOM) as “all organic material in soil including humus”. SOM participates to biological, physical and chemical functions of soil and therefore, presents a crucial role in characterising soil and its processes. For this reason, it can be considered as an “integrating soil parameter indicating soil quality within a given soil series” (Pulleman et al., 2000).

The results of the ANOVA conducted on organic matter content, SOM (%), in soil at 3 depths from the 24 plots constituting the field were presented in Table 8.

Table 8 ANOVA table for SOM of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008.(significant results in bold)

	Degree. of - Freedom	SOM (%) F	SOM (%) p
Intercept	1	2908.46	0.000
Year(Cover*Irrigation*depth)	48	1.09	0.354
Cover	3	1.60	0.194
Irrigation	1	0.06	0.812
depth(Cover*Irrigation)	16	6.34	0.000
Cover*Irrigation	3	0.95	0.421
Error	96		
Total	167		

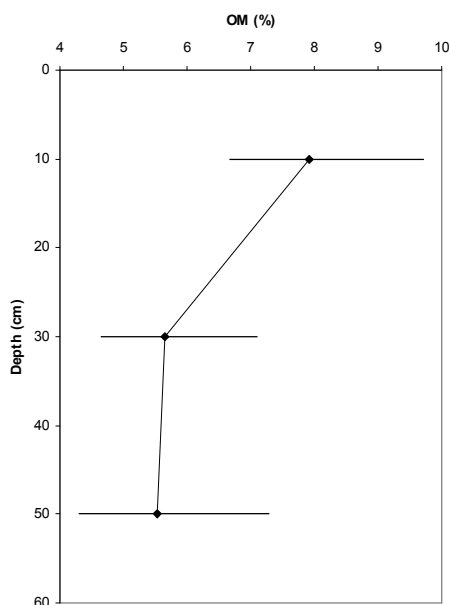


Figure 15 Mean soil organic matter (%) distribution in soil grouped by depth (horizontal bars denotes 0.95 confidence interval).

Only the depth factor had a significant effect on SOM distribution in soil. In particular, neither tree presence nor irrigation significantly changed SOM distribution in soil. At 10 cm depth, SOM (%) was significantly higher (7.91 %) than at 30 cm (5.65 %) and 50 cm (5.52 %). (Figure 15). All the values were comprised between the two soil organic matters target set by DEFRA for 2010 to maintain soil quality (4.8 % for arable rotational grassland and 7.2 % for permanent grassland, DEFRA, H5, 2003). Therefore, they were normal and expected values.

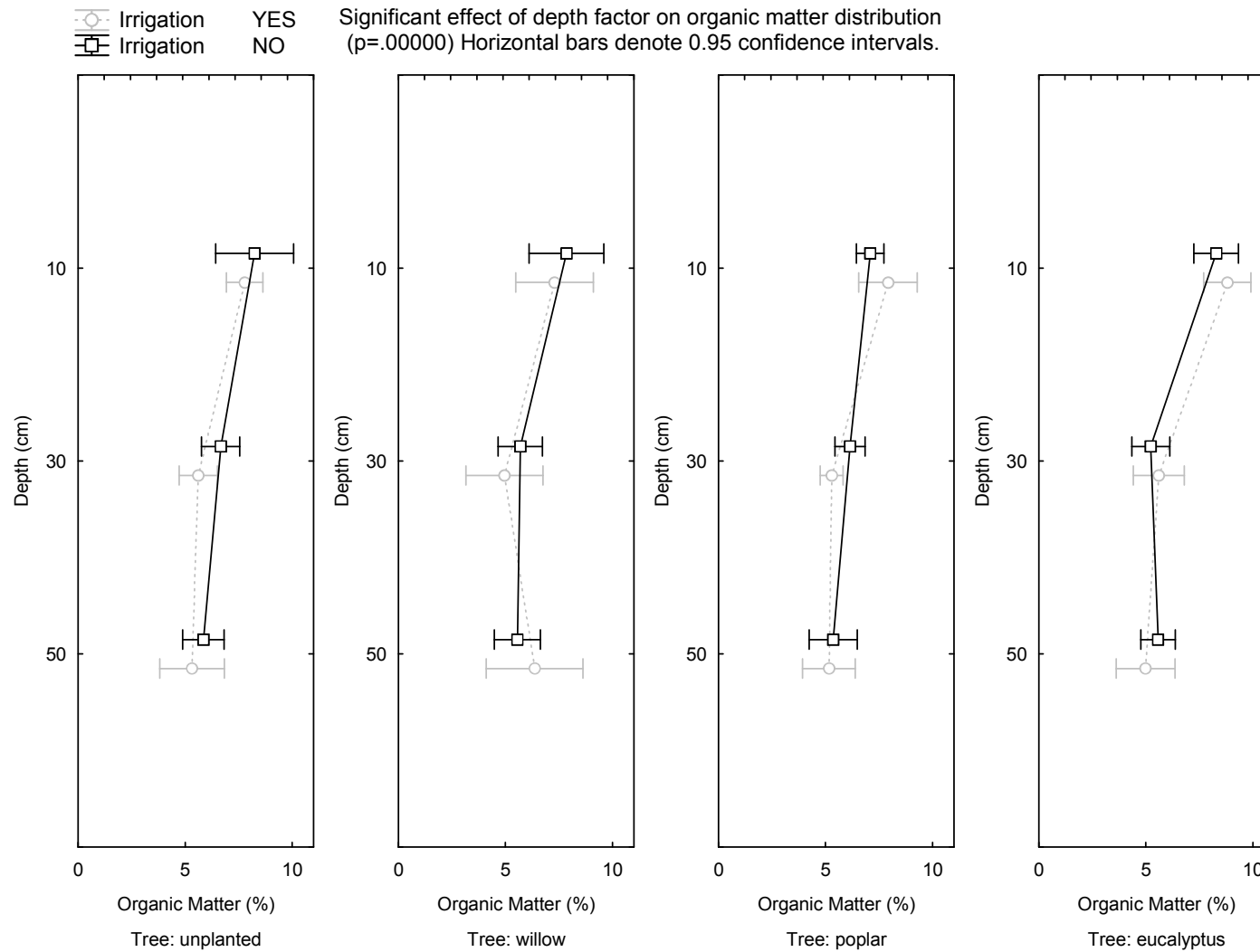


Figure 16 Mean soil organic matter (%) in soil at 3 depths (10, 30 and 50 cm), under 4 covers (unplanted, eucalyptus, poplar and willow) from irrigated or not plots over 3 years (2006, 2007, 2008). The graph is drawn staggered at each depth for clarity

3.8 NITROGEN EVOLUTION IN SOIL

There are 2 major pools of N in soil: the organic pool, not readily available for plant uptake and the inorganic or mineral pool (nitrate, nitrite or TON and ammonium), readily available for plant and leachable (Rowell, 1994).

3.8.1 Total Oxidised Nitrogen and Ammonium

For mineral N, TON and ammonium data residuals could not be normalised even after transformation. For this reason, Kruskal-Wallis ANOVA had to be performed on these data as multiple independent variables samples were compared. The significance of the effects of year, covers, irrigation and depth were considered for mineral nitrogen but the interaction between factors were not assessed.

For both TON and NH_4 , the factors covers, irrigation and depth were not significant. Even though it was not significant, irrigation patterns were different for TON and ammonium, TON accumulated more on non-irrigated plots than on irrigated plots and ammonium accumulated more on irrigated plots than on non-irrigated plots (Figure 17).

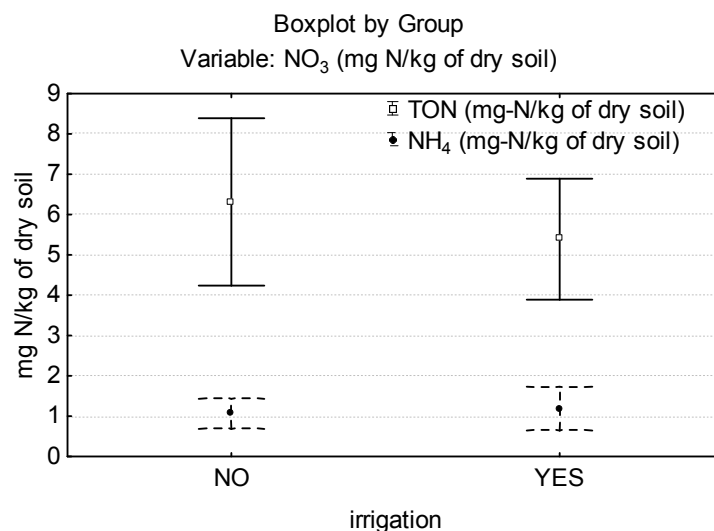


Figure 17 TON and ammonium grouped by irrigation or not (vertical bars denote 0.95 confidence interval).

For both TON and NH_4 , the factor year was the only one with a significant effect. The patterns were the same for both TON and NH_4 : there was a significant decrease in the average concentrations from 2006 to 2007 and an increase, not significant for TON and significant for NH_4 from 2007 to 2008.

First, the evolution of mineral N (defined as the sum of TON and ammonium) in soil from February 2006 to February 2008 was observed. TON represented 92 %, 99 % and then 67 % of the total mineral nitrogen in 2006, 2007 and 2008 respectively. (Figure 18). Section 3.7 with SOM analysis did not reveal a significant increase over the years, however, the decreasing proportion of TON which is represented in TN, reveals an increase in organic N, even though its significance could not be established.

Hence, 2006 mineral N content was 5 times higher than in 2007 and 1.5 times higher than in 2008. It was in accordance with the history of the site; the site has been built in October 2005 and the soil completely disturbed (Chapter 3, 2.1). These disturbances usually cause nitrogen to be released from soil and fertilisation was not advised on the first year after site instalment because of this reason (Tisdale et al., 1999) Indeed, if a soil was ploughed in autumn and left without crops growing on it, mineralisation of nitrogen will happen and there will not be any sink for it like plant uptake, hence this mineralised nitrogen could directly leach during a rainfall event.

The low values of 2007 can be explained by the fact that poplar and willow leaves were removed from site in October 2006 shortly after leaf fall on all plots. However, in autumn 2007, the leaves were left on site after leaf fall and the increase of more than 3 times of total mineral nitrogen can be explained by the incorporation of leaf nitrogen by decomposition of the litter.

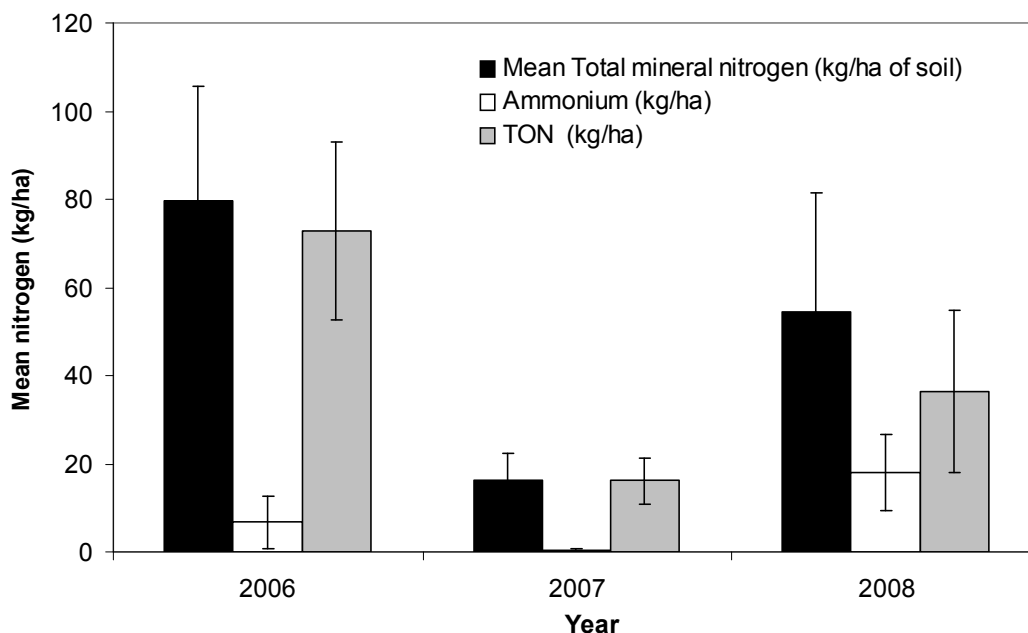


Figure 18 Mineral Nitrogen evolution in soil (total, TON and ammonium) grouped by year (vertical bars denotes standard deviation).

3.8.1.1 TON

In February 2006, the irrigation system had not been installed yet. The higher value of TON in soil in 2006 than 2007 and 2008 is plausible (Figure 18). It can be explained by the fact the previously uncultivated soil was ploughed in October 2005 and the tree cuttings planted at the same time died during the autumn. Moreover, rainfall during autumn and winter 2005-2006 were relatively low compared to the 30 years average (Chapter 3, 2.2, Figure 2). There was a deficit of 56 mm for the period October 2005-February 2006 with a total rainfall for the period of 194 mm. Thus, mineralised nitrogen stayed in place and accumulated, resulting in these high concentrations.

Now, between 2006 and 2007 reduction can be explained by 3 points. The processes capable of consuming TON in soil are volatilisation by denitrification into N_2 and NO_x uptake by plants, and leaching into groundwater (DEFRA, 2002; Conrad et al., 1983). First, as there is no significant difference between irrigated and non-irrigated averages, the rainfall for the period, 2006 was a wet year compared to the 30 years average data (from November 2006 until February 2007, the monthly rainfall recorded were over the 30 years average), hence, mineralised nitrogen was transported and leached out the 50 cm depth of sampling. Second, there were crops growing, the trees were a year old

and therefore significantly developed in February 2007. Third, during autumn 2006, leaves were removed shortly after leaf fall so that all the nitrogen uptaken by the plants didn't come back into the soil system and were effectively exported.

Finally, the non significant enrichment between 2007 and 2008 can be explained by 2 points. First, there is no significant difference between averages under irrigated plots and non-irrigated plots; however, irrigated plot concentration was lower. Because of more water applied, more water left the profile, taking away mineralised nitrogen. Second, during autumn 2007, leaves were left on soil surface and contributed to increase mineralisable organic matter.

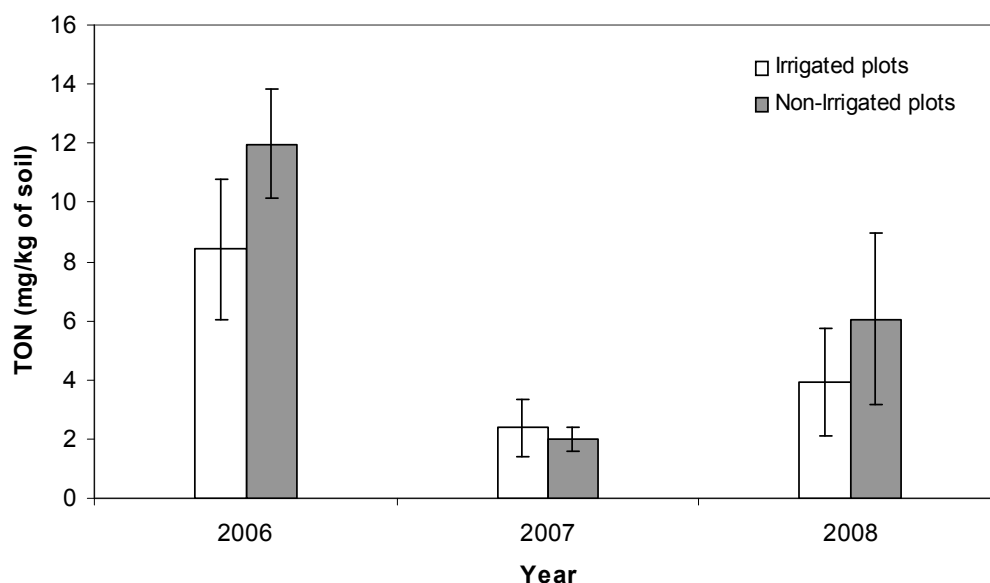


Figure 19 Mean TON regrouped by year and irrigation. Vertical bars denote 0.95 confidence interval calculated with yearly standard deviation.

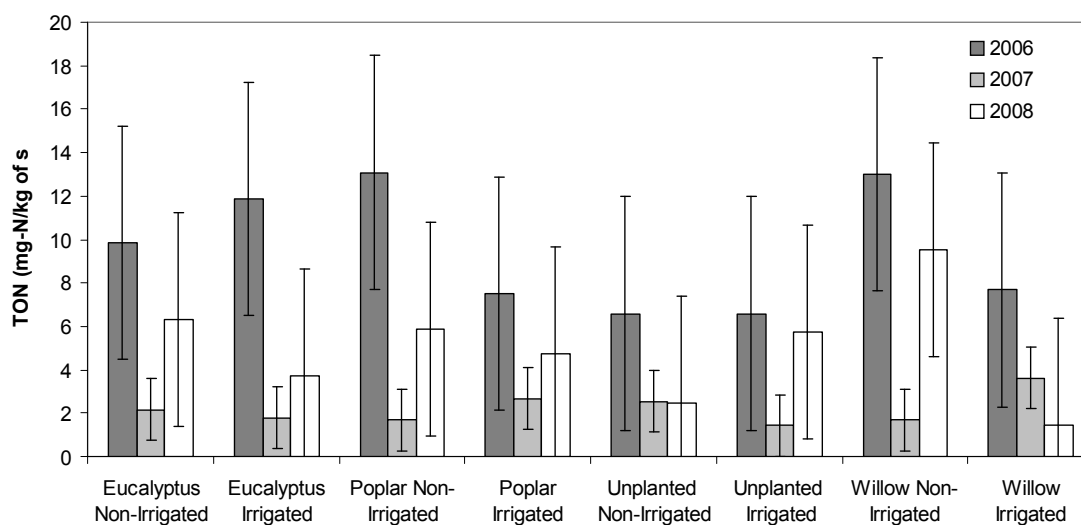


Figure 20 Comparison of TON measurements from the selected plots with vertical bars to denote 0.95 confidence interval calculated from standard deviation of all the measurements on a year.

Means of TON were calculated using measurements regrouped by year and irrigated or not. 0.95 confidence intervals were calculated using standard deviation from year and irrigation (Figure 20). TON was increased only on unplanted plots, but not even significantly, by irrigation in 2008.

The yearly trends (Figure 19) are dictated by poplar and willow TON concentrations (Figure 20). Indeed, non-irrigated poplar and willow presented higher values for 2006 and 2008 than irrigated concentrations and they were directly reflected in the yearly averages. Within a same cover and irrigation application, the reductions from 2006 to 2007 were significant for eucalyptus, irrigated and non-irrigated, poplar non-irrigated, and willow non-irrigated. Hence, tree presence accentuated the reduction even though not significantly.

3.8.1.2 Ammonium

There was a significant reduction in ammonium concentration of the soil profile between 2006 and 2007 (Figure 21). The processes capable of consuming ammonium in soil are volatilisation to NH_3 , nitrification (to nitrite and then nitrate), uptake by plants, and fixation to clay as part of cation exchange capacity (Rowell, 1994; Tisdale et al., 1999). There was an enrichment in ammonium in soil profile between 2007 and 2008. It was significant for irrigated eucalyptus and willow planted plots and non-irrigated unplanted and willow planted plots. Hence, this increase could not be attributed clearly to trees or to irrigation, or to the combination of both. But the trends for ammonium evolution year by year were the same as for TON. However ammonium concentrations were greater in 2008 than in 2006. These high 2008 concentrations could be explained by 2 factors, first in autumn 2007, leaves were left to decompose on each plot, allowing their mineralisation which includes ammonification (Rowell, 1994; Tisdale et al., 1999) unlike autumn 2006, during which leaves were collected shortly after their fall. The second event is the time between the last effluent application and the date of soil collection; there was an intensive irrigation period in January 2008 and it was stopped only a week before soil sampling but in 2007, the last effluent application took place in October 2006, therefore 4 months earlier. But as the increase in ammonium concentration was greater under non-irrigated plots in 2008, mineralisation might have had a greater role.

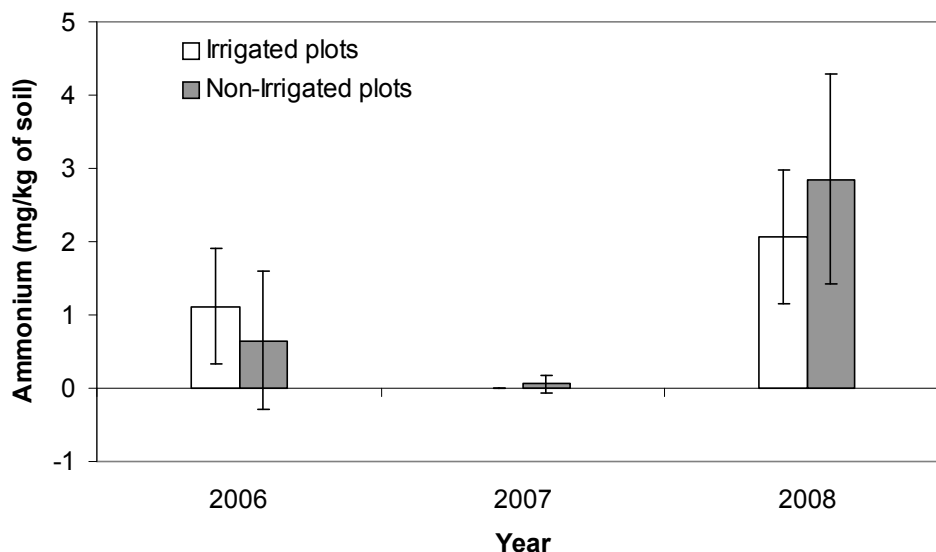


Figure 21 Mean Ammonium regrouped by year and irrigation. Vertical bars denote 0.95 confidence interval calculated with yearly standard deviation.

3.8.2 Total Nitrogen (TN, g.kg⁻¹ of soil)

Total nitrogen, TN represents the sum of organic N and mineral N (Tisdale et al., 1999) (Equation 4).

$$\begin{aligned} \text{Total nitrogen} &= \text{Organic } N + \text{Mineral } N \\ \text{Mineral } N &= \text{TON} + \text{Ammonium} \end{aligned} \quad \text{Equation 4}$$

The results of the ANOVA conducted on Total Nitrogen (including both organic and mineral N), TN, in soil at 3 depth, 10 cm, 30 cm and 50 cm, from the 24 plots constituting the field trial are presented in Table 9.

The only factor with a significant effect on TN concentrations was the depth factor. In other words, neither irrigation with secondary treated effluent, tree presence nor natural soil evolution had a significant effect on TN concentration in soil.

Table 9 ANOVA table for TN of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008.

	Degree. of - Freedom	TN (g/kg of soil) - F	TN (g/kg of soil) - p
Intercept	1	1771.59	0.000
Depth(Cover*Irrigation)	16	5.78	0.000
Cover	3	0.51	0.679
Irrigation	1	0.03	0.874
Year(Depth*Cover*Irrigation)	48	1.03	0.436
Cover*Irrigation	3	1.35	0.263
Error	96		
Total	167		

According to the LSD (Least significant difference) table and Figure 22, TN concentrations at 10 cm depth for either irrigated or un-irrigated plots, under all the covers, were significantly higher than at 30 cm and 50 cm. However, even if concentrations at 30 cm were higher, they were not significantly higher than at 50 cm.

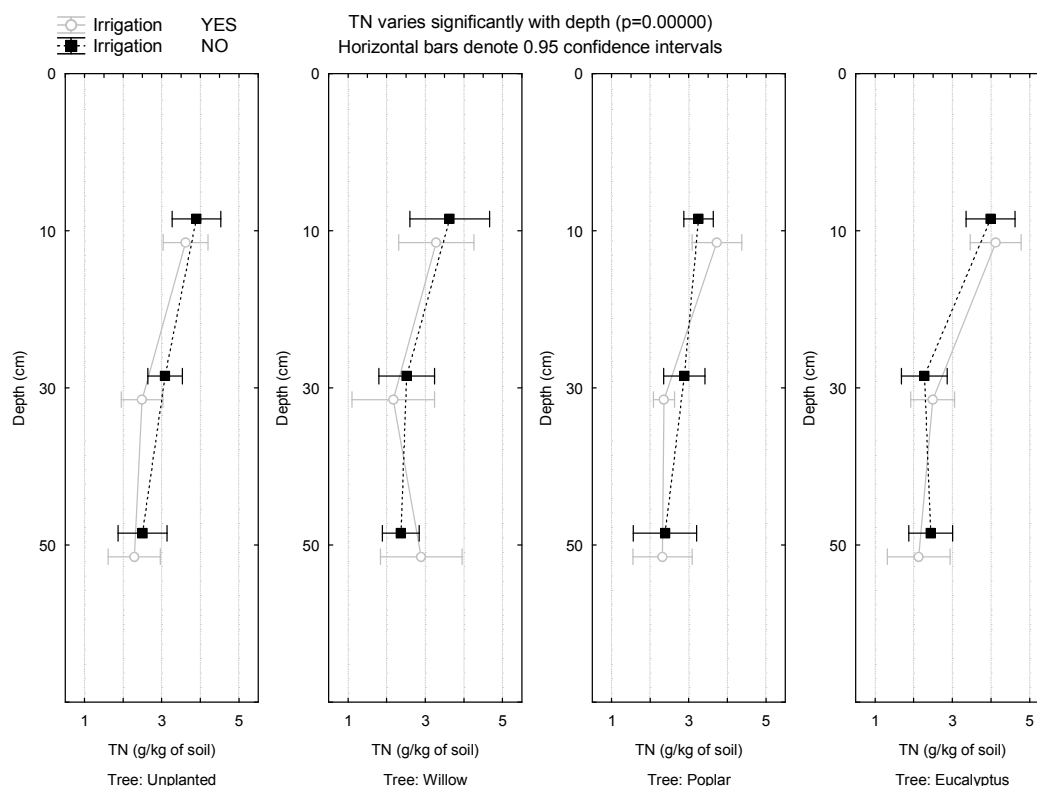


Figure 22 TN distribution under the 4 different covers (willow, poplar, eucalyptus, and unplanted) irrigated or not, grouped by depth (10 cm, 30 cm and 50 cm). The graph is drawn staggered at each depth for clarity

For all plots, at all depths, there was no irrigation effect. Moreover, even if not significantly, TN distributions by depth were different for planted and unplanted plots. The concentrations seem to be lower at 30 cm on planted plots than on unplanted plots. The explanation would be that a greater TN uptake took place on planted plots as the maximum root density zone for the trees species grown was around 30 cm (Trindade et al., 1997, Spangenberg and Kolling, 2004). Even if it was not significant, TN concentrations in plots planted with trees were higher than on unplanted plots (Figure 30). The evolution during the 3 years was different as well between unplanted and planted plots; there was a gradual enrichment of TN on the whole profile for tree planted plots but not for unplanted plots (Figure 23).

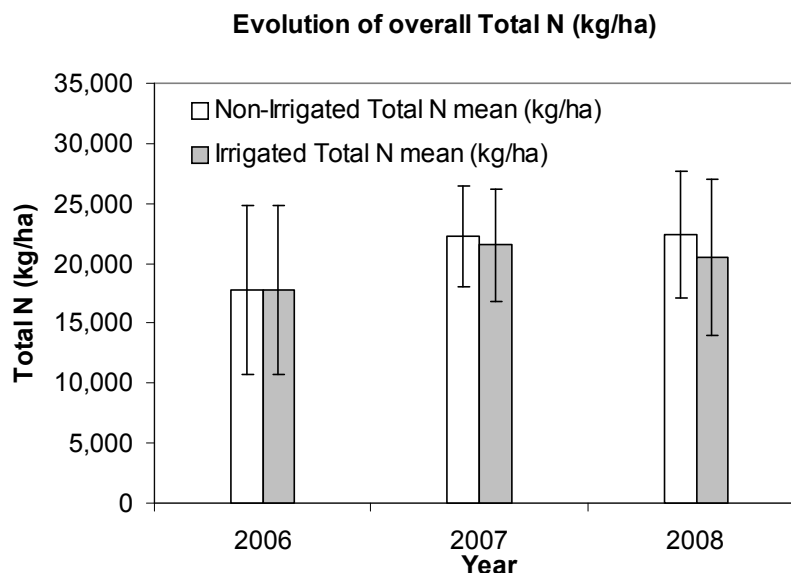


Figure 23 TN evolution grouped by year and irrigation or not. (\pm standard deviation)

It has to be underlined that TON and ammonium concentrations were expressed in mg.kg^{-1} of soil (with maximum values up to 12 mg.kg^{-1} of soil) but TN concentrations were expressed in g.kg^{-1} of soil, ranging from as little as 2.13 g.kg^{-1} of soil (in unplanted irrigated 50 cm depth sample) to 4.12 g.kg^{-1} of soil (in eucalyptus irrigated 10 cm depth sample). Therefore the organic N pool (as the difference between TN and mineral N) is the major constituent of TN in soil as it represents over 99.95 % of it. N was essentially applied as TON (accounting for more than 80 % of TN applied); i.e. as mineral N. The amounts of TON applied ranged from 385 kg.ha^{-1} to 1036 kg.ha^{-1} for the whole period of the experiment (Table 1, Section 3.1). The average amount of TN in soil from 0-60 cm in 2006 was of $17,800 \pm 3,371 \text{ kg.ha}^{-1}$ (Figure 23). So that irrigated N accounted for 2 % to 6 % of the TN present in soil. Therefore, it was expected not to find a significant effect of irrigation on TN concentrations in soil during this experiment.

In chapter 4 (3.4.2 Table 16 and 18) TN uptakes were assessed to be ranging from 74 kg-N.ha^{-1} (for poplar or 10.11 mg kg^{-1} of soil when the layer of soil from 0-60 cm is considered) to 264 kg-N.ha^{-1} (for eucalyptus for 36.07 mg kg^{-1} of soil when the layer of soil from 0-60 cm is considered) for wood over the whole experiment. The amounts uptaken were low compared to the proportion of TN present in soil in 2006. They represented less than 2 % of TN present in soil in 2006 in 0-60 cm depth profile (0.4 % to 1.5 %). Therefore, it was expected not to find a significant effect of tree presence on TN concentrations in soil.

There was an initial heterogeneous distribution of TN with depth. There were higher TN concentrations on the surface and it was mainly organic N. As organic matter gets deposited from the surface, this distribution is expected. And irrigation or tree presence or their interaction did not alter significantly this initial distribution.

3.9 PHOSPHORUS EVOLUTION IN SOIL (TOTAL AND OLSEN)

3.9.1 Olsen-P or plant available P

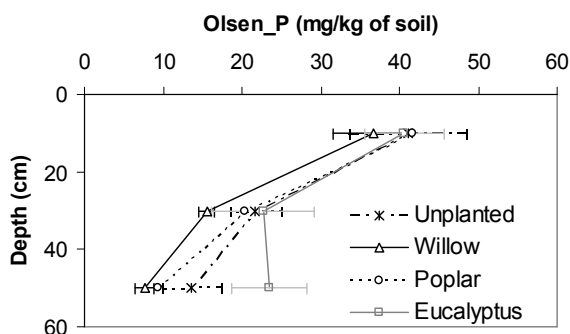
Olsen-P represents the plant available P and the inorganic phosphate pool of total phosphorus (Rowell, 1994). ANOVA was performed and results are presented in Table 10. Only the factor depth had a significant effect (Table 10). Irrigation with secondary treated effluent, tree presence or natural soil evolution did not have a significant effect on Olsen's P concentration in soil.

Table 10 ANOVA table for Olsen's P concentration of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008.

	Degree of - Freedom	Olsen_P mg/kg - F	Olsen_P mg/kg – p
Intercept	1	417.97	0.000
Cover	3	0.19	0.901
Irrigation	1	0.35	0.553
year(Cover*Irrigation*depth)	42	1.17	0.262
depth(Cover*Irrigation)	16	5.34	0.000
Cover*Irrigation	3	0.73	0.534
Error	95		
Total	160		

According to the LSD (Least significant difference) table, Olsen's P concentrations at 10 cm depth for all plots were significantly higher than at 30 cm and 50 cm. However, even if concentrations at 30 cm were higher, they were not significantly higher than at 50 cm (Figure 24). Then, only the willow irrigated plot at a 10 cm depth Olsen's P concentration was not significantly higher than at 30 cm and 50 cm depth.

Non-Irrigated



Irrigated

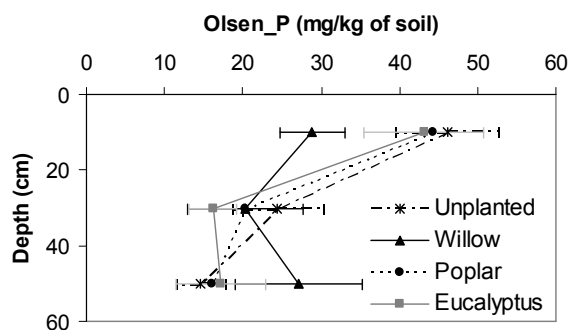


Figure 24 Mean Olsen's P concentration on the average between irrigated and non-irrigated plots covered with willow, poplar, eucalyptus and unplanted (horizontal bars denote standard deviation).

P was applied by irrigation mainly as phosphates (Section 3.1.2). The maximum amount applied was for willow 2007 with 93 kg-P ha^{-1} (12.70 mg.kg^{-1} of soil¹). The average P application on planted plots for 2006 was $42 \pm 9 \text{ kg-P.ha}^{-1}$ (5.74 mg.kg^{-1} of soil), 29 kg-P.ha^{-1} (3.96 mg.kg^{-1} of soil) for unplanted plots and for 2007 was $86 \pm 8 \text{ kg-P.ha}^{-1}$ (11.75 mg.kg^{-1} of soil) for planted plots, 24 kg-P.ha^{-1} (3.28 mg.kg^{-1} of soil) for unplanted plots. And these amounts were lower than the recommendations from RB 209 for soil presenting initial P index of 2 (Section 3.1.2).

¹ 1 ha of soil was converted to 7,320 tonnes of soil as a layer of 0-60 cm soil was considered.

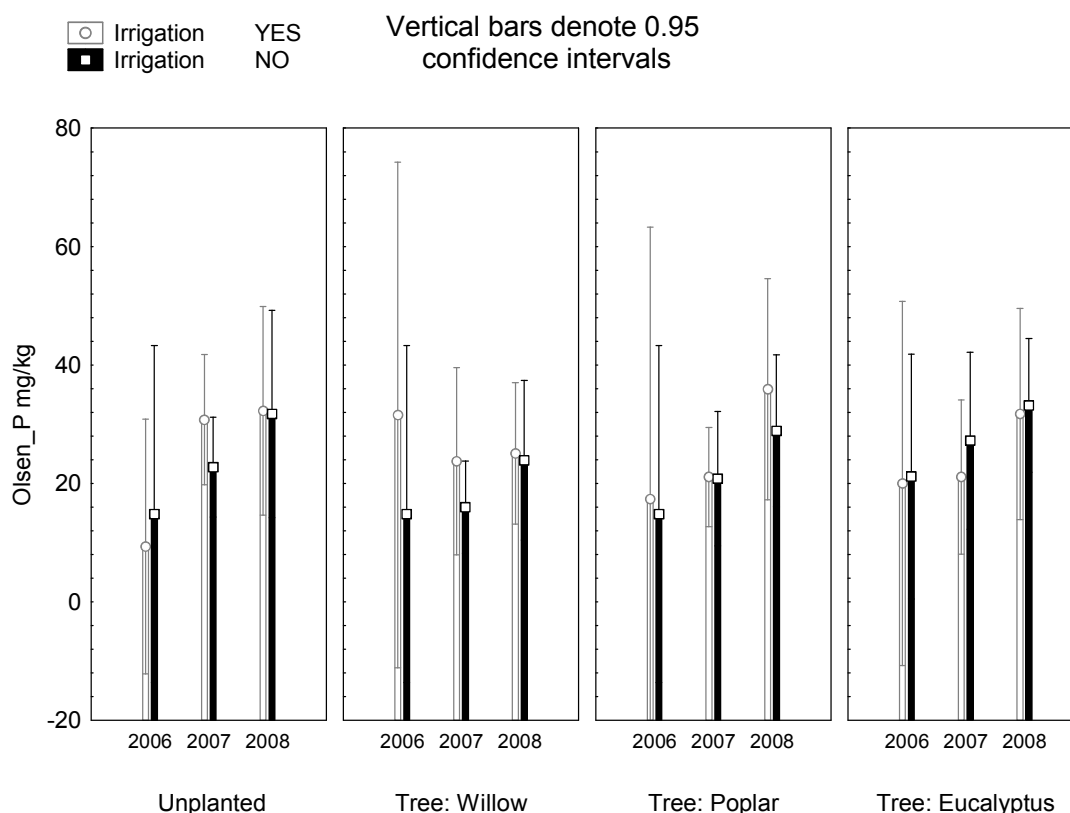


Figure 25 Evolution of Olsen-P in soil (from 0-60 cm depth) averaged by year, irrigation and covers.

The amounts of P applied in 2006 represented 29 % of the Olsen-P present in soil in February 2006 for planted plots and 20 % for unplanted. And for 2007, the amounts of P applied in 2007 represented 49 % and 14 % of Olsen-P present in soil in February 2007 for planted and unplanted plots respectively (Figure 25). Moreover, as phosphate minerals present very low solubility and very high affinity to bind to soil particles, it was surprising, in regard to the amounts of phosphate applied, that irrigation did not have a significant effect on increasing Olsen-P in soil during the experiment.

When P was uptaken by plants, it was in the Olsen-P form. Chapter 4 (section 3.4.2, Table 18) presented the amounts of P uptaken by plants during the whole experiment. These P uptakes, compared to P applied by irrigation, represent 38 % for eucalyptus, 12 % for poplar and 24 % for willow. Therefore, it was also surprising that tree presence did not have a significant effect on lowering P compared to unplanted irrigated plots. There should be another source of Olsen-P in soil and TP will be discussed in the next section.

Statistically, tree presence and/or irrigation with secondary treated effluent didn't increase significantly Olsen-P in soil profile. Only in the case of Willow planted plots, irrigation lowered significantly Olsen-P at 10 cm so that the whole soil profile considered from 0 cm to 60 cm would present an average Olsen-P of $25.4 \text{ mg-P.kg}^{-1}$ of soil. In all other plots, the initial heterogeneity of available P distribution (Figure 26, $42.2 \pm 3.3 \text{ mg-P.kg}^{-1}$ of soil at 10 cm, $20.2 \pm 0.15 \text{ mg-P.kg}^{-1}$ of soil at 30 cm and $42.2 \pm 1.7 \text{ mg-P.kg}^{-1}$ of soil at 50 cm depth) was maintained by irrigation and cover as natural evolution of soil. However, there was an enrichment of every layer in general apart from irrigated willow. As it was observed for both irrigated and non-irrigated plots, irrigation alone can not explain these increases. Hence, there was a secondary source of P release as mineralisation of organic P would be increasing rather than decreasing as organic turnover is stimulated by tree growth (Rowell, 1994). However, in autumn 2006, leaves were collected after leaf fall but not in autumn 2007, therefore, it would explain Olsen-P increase under planted non-irrigated plots. (Rowell, 1994) reported that Na saturation of soil would induce more P to be extractable from soil. As Na was applied with irrigation with application rates up to $1.4 \text{ tonne.ha}^{-1}.\text{year}^{-1}$, these progressively increased for irrigated plots but not for non-irrigated ones.

In relation to risk of P leaching out from soil into drainage water, average for each depth, covers and irrigated or not was compared to the threshold limit identified by (Sharpley et al., 1988) of 60 mg-P.kg^{-1} of soil of Olsen-P up to which, P leaching can happen. Thus, all the values for 2008 at 10 cm depth are close but lower than the 60 mg-P.kg^{-1} of soil except for irrigated poplar ($60.3 \text{ mg-P.kg}^{-1}$ of soil). However, because of variability in replicates, this Heckrath threshold was comprised within the confidence interval. (cf. Figure 26, 27).

In the literature, P fate modelling was presented as challenging as processes are happening at different time scales (Heckrath et al., 1995). In particular a linear regression on 2 values between P applied and subsequent Olsen-P build up would not be representative of reality. A complementary experiment was set up and run in order to understand P fate after application to soil (Chapter 8).

As more P was uptaken by trees than applied by irrigation, Olsen-P was expected to decrease rather than increase as observed. It was not possible to understand at this stage why there was a progressive increase of Olsen-P at all depths, even though not significant.

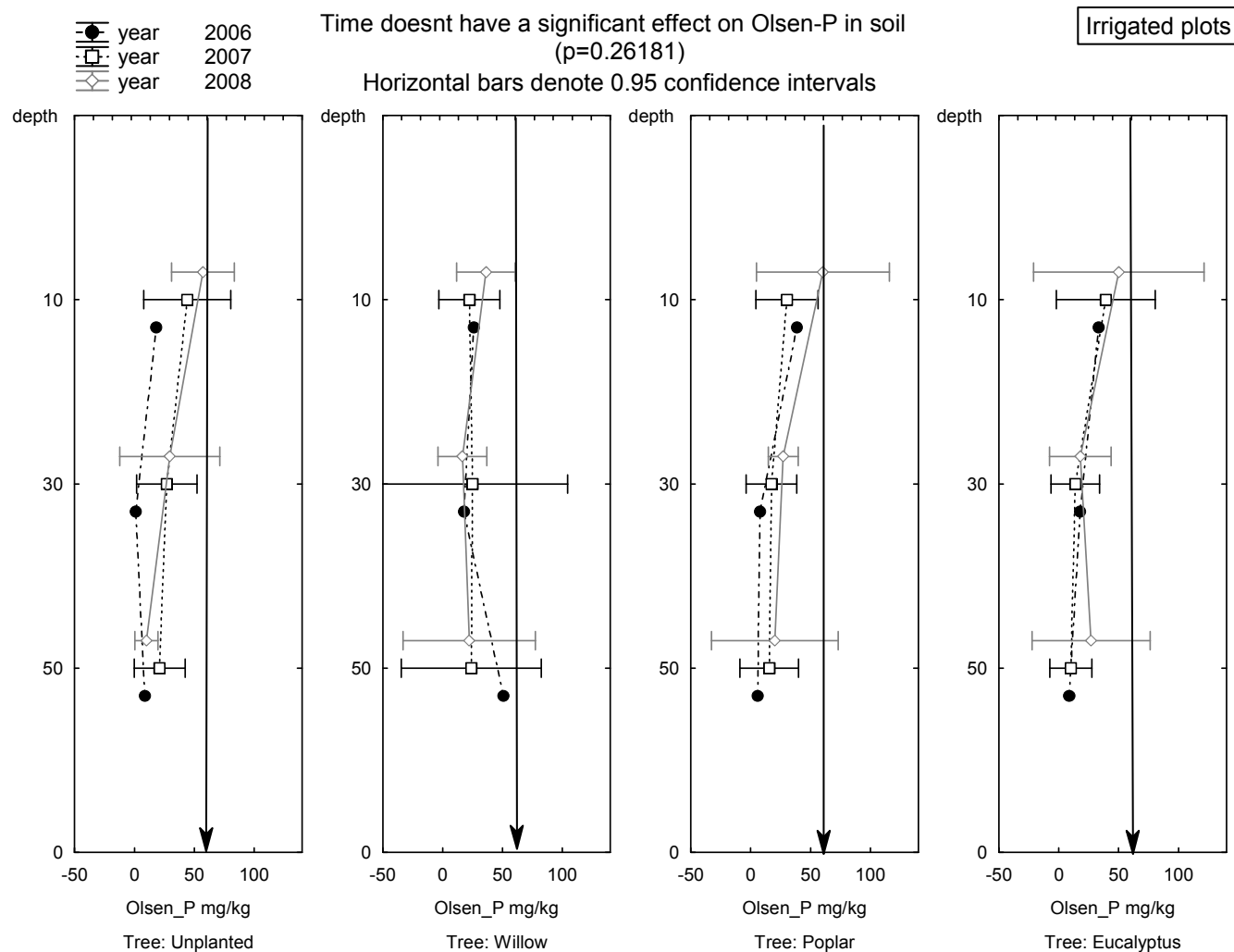


Figure 26 Olsen-P evolution in soil at 3 depths (10, 30 and 50 cm), under 4 covers (unplanted, eucalyptus, poplar and willow) irrigated from February 2006, 2007 and 2008. Vertical line (–) represents 60mgP/kg of soil identified as change point concentration before Phosphorus can be detected in drainage water (Mamo et al., 2005; McGechan and Lewis, 2002/5; McGechan, 2002/6).

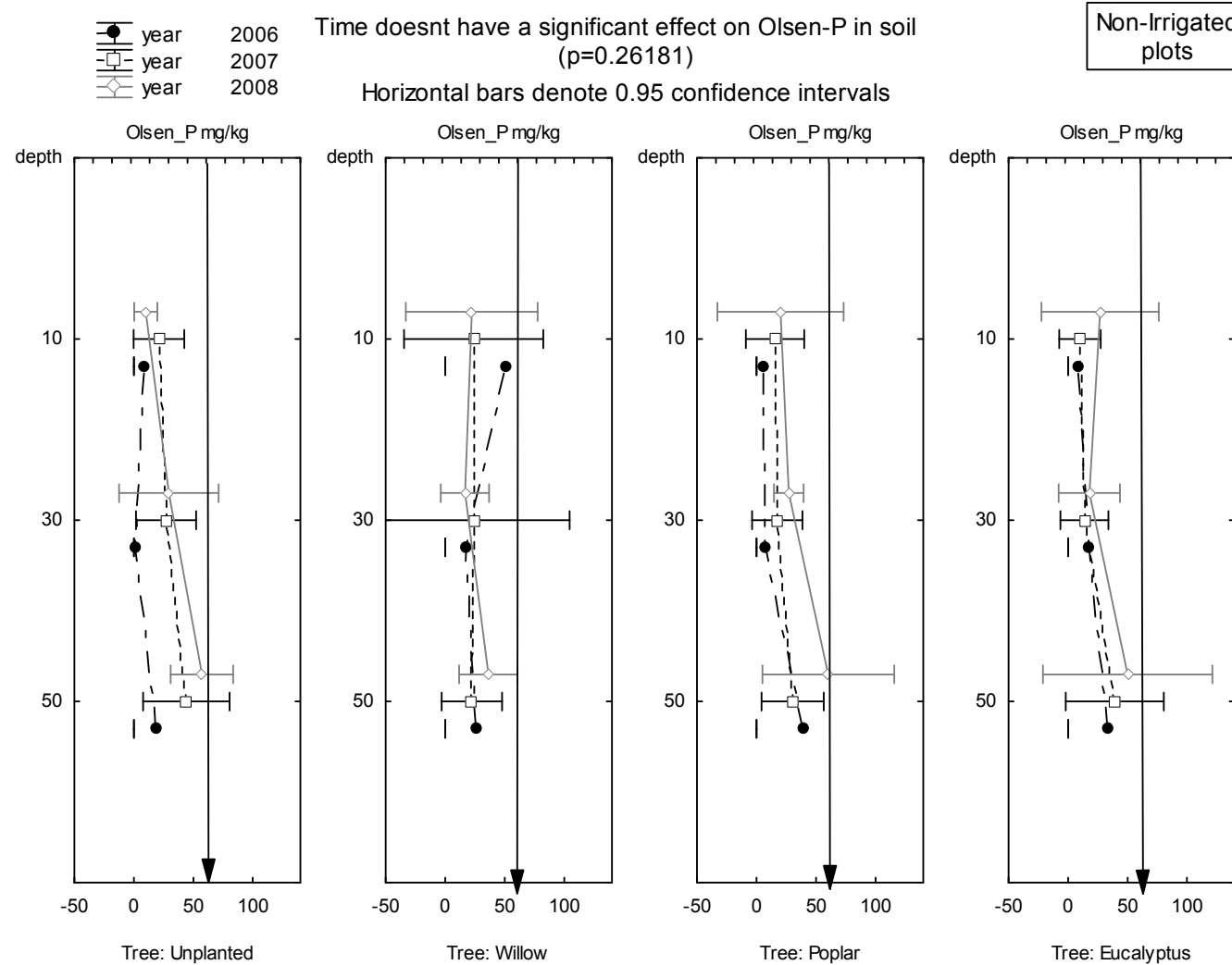


Figure 27 Olsen-P evolution in soil at 3 depths (10, 30 and 50 cm), under 4 covers (unplanted, eucalyptus, poplar and willow) non irrigated from February 2006, 2007 and 2008. Vertical line (\rightarrow) represents 60mgP/kg of soil identified as change point concentration before Phosphorus can be detected in drainage water (Brookes et al., 1997).

3.9.2 Total Phosphorus (TP, g.kg⁻¹ of soil)

The definition for TP used in this study is the one proposed in (Brookes et al., 1997) and was reported as presented by (Pierzynski, 2000), Table 1 p 3.

$$TP = TDP + PP$$

with $\left\{ \begin{array}{l} TP: \text{Total phosphorus, total amount of P in dissolved and particulate phases} \\ TDP: \text{total dissolved phosphorus, dissolved inorganic (OrthoP) and organic P} \\ PP: \text{particulate phosphorus, inorganic and organic P associated with or bound to} \\ \quad \text{eroded sediment} \end{array} \right.$

Olsen-P is constituted by dissolved inorganic ortho-P and the bio-available particulate P (Pierzynski, 2000). According to the ANOVA table (Table 11), the factors depth and year were the only factors with a significant effect on TP concentrations. In particular, irrigation with effluent and tree presence didn't influence soil TP significantly.

Table 11 ANOVA table for TP of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008.

	Degree. of - Freedom	TP mg/kg - F	TP mg/kg - p
Intercept	1	1292.94	0.000
Cover	3	1.38	0.253
Irrigation	1	0.42	0.517
year(Cover*Irrigation*depth)	48	1.55	0.025
depth(Cover*Irrigation)	16	1.91	0.024
Cover*Irrigation	3	0.50	0.680
Error	146		
Total	217		

There was a progressive build-up of TP from 2006 to 2008 (Figure 28). This build-up happened on both irrigated and non-irrigated plots. There were no significant differences between irrigated and non-irrigated TP concentrations under the same covers. Hence irrigation didn't significantly increase TP concentrations even though they were higher (LSD table). There was a lot of variability (0.95 confidence interval bars around a third of the means) because of the great variability of TP with depth; indeed average TP at 50 cm corresponded to 80 % of TP at 10 cm and 89 % of TP at 30 cm.

TP in soil averaged by cover and irrigation in 2006 for the 0-60 cm layer was $812 \pm 250 \text{ mg.kg}^{-1}$ of soil and TP in soil averaged by cover for irrigated plots was $866 \pm 143 \text{ mg.kg}^{-1}$ of soil (Figure 28). On converting the cumulative amount of P applied by irrigation during both irrigation seasons, in 2006-2007, TP was applied at a rate of 5.26 mg/kg of soil (values are given for the 0-60 cm layer) and in 2007-2008, 9.67 mg/kg of soil (values are given for the 0-60 cm layer¹) of TP was applied. Therefore, TP applied by irrigation corresponded to less than 0.7 % in 2006 and 1 % in 2007 of the TP already present in soil. Hence, an irrigation effect on TP concentration was not expected as confirmed by ANOVA results (Table 11). On considering the amount uptaken by plants as calculated in section 3.9.1 and Chapter 4 (section 3.4.2, Table 18) for the 2 seasons as 4.4 mg.kg^{-1} of soil for eucalyptus, 1.4 mg.kg^{-1} of soil for poplar and 2.8 mg.kg^{-1} of soil for willow. And these amounts represented 38 % for eucalyptus, 12 % for poplar and 24 % for willow of P applied. Therefore, as for Olsen-P, tree presence was not expected to have a significant effect as confirmed by ANOVA results (Table 11).

Furthermore, comparing to the values of Figure 28, the enrichment of TP on the 60 cm layer was of 80 mg.kg^{-1} per year. Therefore, TP applied by effluent couldn't explain the annual enrichment. Moreover, the fact the yearly enrichments were of the same range for both years could enhance the idea of a process independent of irrigation. The factor year increased TP significantly according to ANOVA table (Table 11). But according to LSD table, there were no significant increases when one type of cover with one type of irrigation (irrigated or not irrigated) was considered year by year. As these increases were not expected and the amounts added were too low to explain them and these increases had to come from another sources, the method of TP determination could be questioned. The method chosen in this study to determine TP is aqua regia digestion in closed microwave (Chapter 3, 6.1.2) (Pierzynski, 2000) reported this method might underestimate TP amounts in soil as it fails to extract all P in apatite inclusions. The other processes involved might be mineralisation of organic P and natural clay chemical weathering. Clay weathering would lead to enhanced mineralisation subsequent to heavy, high intensity rainfall. The rainfalls data for the duration of the experiment confirmed wetter conditions (2006 annual average was 605 mm with over 90 mm.month^{-1} for May, August and November, 714 mm for 2007

¹ 1 ha of soil was converted to 7,320 t of soil as a layer of 0-60 cm soil was considered.

with over $100 \text{ mm} \cdot \text{month}^{-1}$ for May, June, July and November) than the 30 years average of 577 mm (Chapter 3, 2.2, Figure 2).

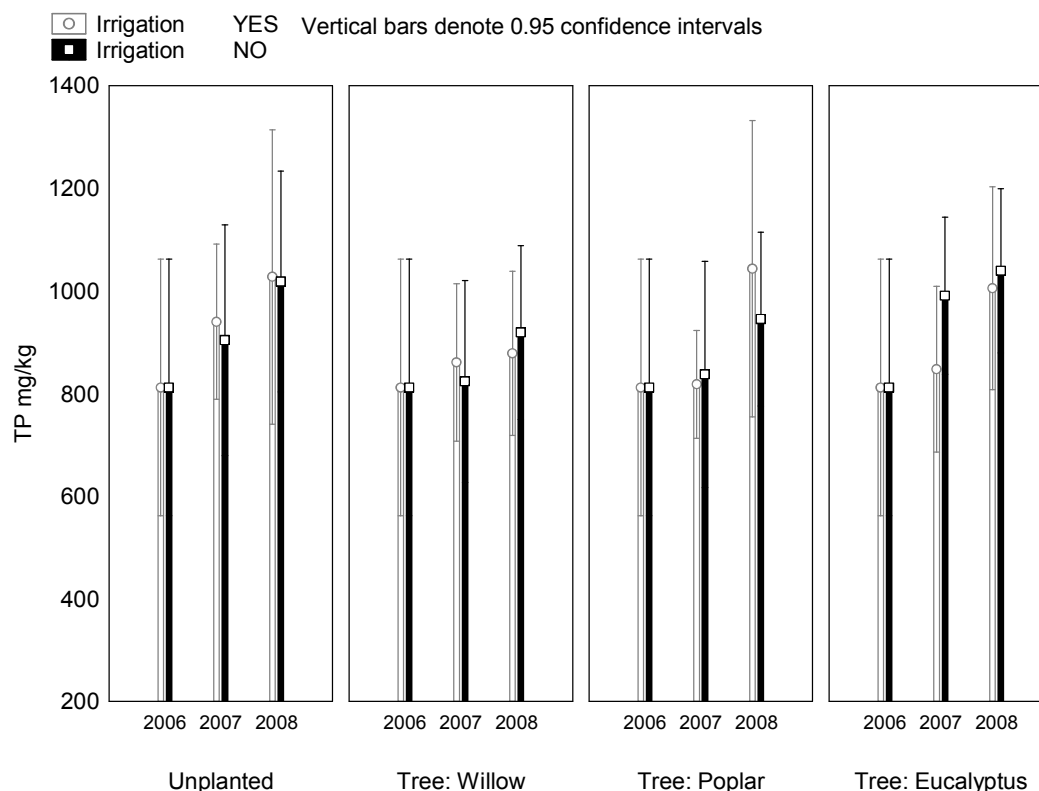


Figure 28 Evolution of average TP concentration under all covers from 2006 to 2008, under irrigation with secondary treated effluent or not.

There was also an initial heterogeneity in TP concentration distribution with depth; with higher concentration on surface and gradually lower concentration with depth (Figure 29, 30). Their evolution was different from depth to depth (Figure 29, 30). And even though not significant, at 30 cm, irrigated plots presented a higher TP concentration and a lower one at 50 cm so that the average amount of TP in the whole profile from 0-50 cm were comparable between irrigated and non-irrigated plots (Figure 29, 30). 10cm depth TP evolutions will be looked at in details in this paragraph. From 2006 to 2007, there is a decrease in all plots, irrigated or not. But then, there was an increase on all plots from 2007 to 2008. The changes were greater on irrigated plots than on non-irrigated, even though irrigation didn't make these differences significant. The installation of a WaterRenew system did not have any significant effect on TP concentrations in soil until 50 cm. In particular, irrigation with wastewater did not increase

significantly TP content in the soil profile. On the other hand, tree presence and uptake of phosphorus did not significantly decrease TP content in soil until 50 cm depth. Hence, on both points of view, short rotation coppice (SRC) and wastewater application, the Water Renew system did not have any significant impact. This statement is confirmed by Olsen-P evolution in soil profile.

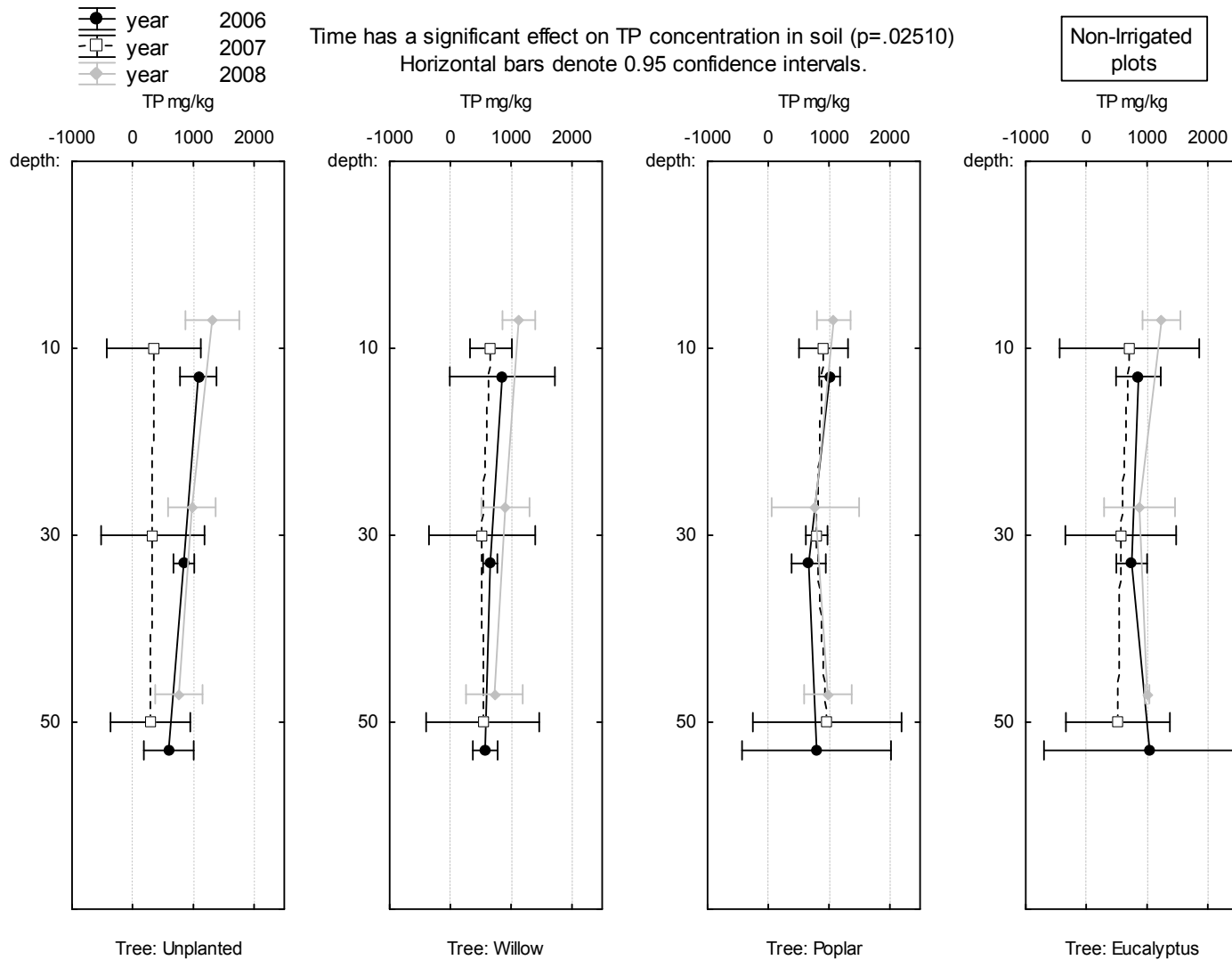


Figure 29 Total-P evolution in soil at 3 depths (10, 30 and 50 cm), under 4 covers (unplanted, eucalyptus, poplar and willow) irrigated from February 2006, 2007 and 2008. The graph is staggered at each depth for clarity.

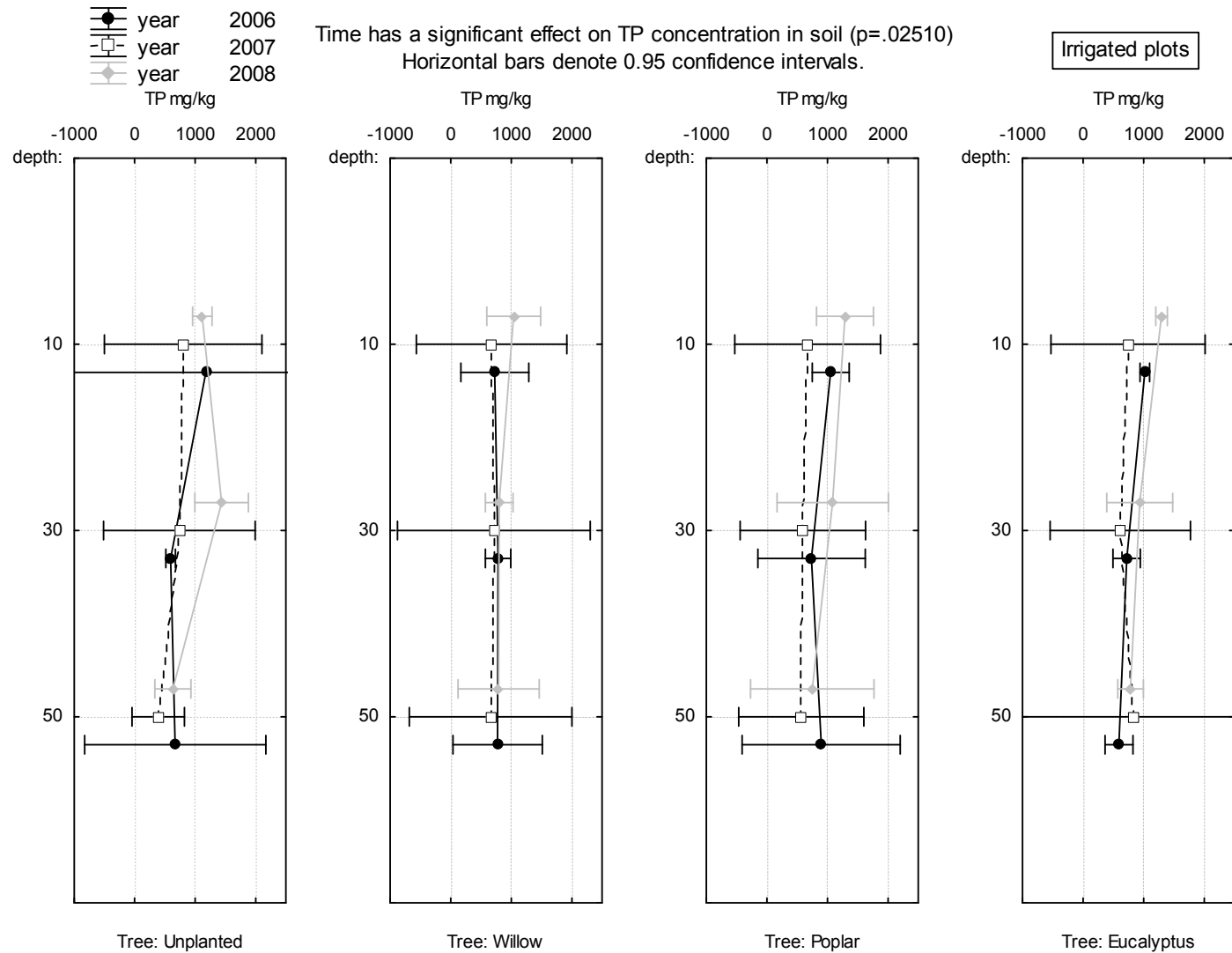


Figure 30 Total-P evolution in soil at 3 depths (10, 30 and 50cm), under 4 covers (unplanted, eucalyptus, poplar and willow) non irrigated from February 2006, 2007 and 2008. The graph is drawn staggered at each depth for clarity.

3.10 POTASSIUM EVOLUTION IN SOIL (TOTAL AND AVAILABLE)

Potassium pool in soil was defined as divided into 3 pools (Bender and Wood, 2000; Syers et al., 1967):

$$TK = \text{unavailable } K + \text{slowly available } K + \text{available } K$$

with $\left\{ \begin{array}{l} TK : \text{Total potassium, total amount of } K \text{ in soil and soil solution} \\ \text{unavailable } K : 90 \% \text{ to } 98\% \text{ of } TK \\ \text{slowly available } K : \text{nonexchangeable form of } K \\ \text{available } K : \text{exchangeable and soil solution } K \text{ and available to plant uptake} \end{array} \right.$

TK and available K pools were studied in these sections.

3.10.1 Available Potassium

ANOVA was performed on log transformed available potassium, K_{av} , data. The factors cover, depth, year and interaction between cover and irrigation were significant but not irrigation itself (Table 12, $p < 0.05$).

Table 12 ANOVA table for available K concentration of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008. (in bold $p < 0.05$)

	Degree. of - Freedom	K_{av} mg/kg of soil F	K_{av} mg/kg of soil p
Intercept	1	223212.6	0.000
cover	3	7.2	0.000
irrigation	1	2.1	0.147
depth(cover*irrigation)	48	12.9	0.000
year(depth*cover*irrigation)	16	6.9	0.000
cover*irrigation	3	23.8	0.000
Error	138		
Total	209		

The amount of K applied by irrigation ranged from 184 mg.kg⁻¹ of soil for unplanted plots to 302 mg.kg⁻¹ of soil for willow plots (Section 3.1, Table 1). The amount applied corresponded to 16 % to 26 % of available K in soil. For 2007, the proportion of applied K to available K in soil in 2007 was of 30 % for willow plots, 35 % for poplar planted plots, and 36 % for eucalyptus planted plots and 8 % for unplanted plots. Hence, the amounts K applied were relatively important and a significant effect of irrigation on available K distribution in soil could have been expected. However, only 10 % of soil K

is in an available form, and total potassium evolution will be assessed in the next section.

The cover influenced significantly the enrichment of the profile in available K (Figure 31). Available K in soil under poplar was significantly lower than under the different covers. This is mainly due to the initially very low K content under those plots (even before any treatment or installation was performed) (Figure 33, 34). However, available K under willow, eucalyptus and in particular unplanted plots were not significantly different. According to Chapter 4 (section 3.4.2, Table 18), K uptakes corresponded to 4.3 % to 18 % of available K in 2006 was uptaken in total during the 2 years of experiment. Hence, a cover effect, especially significant under poplar was not expected.

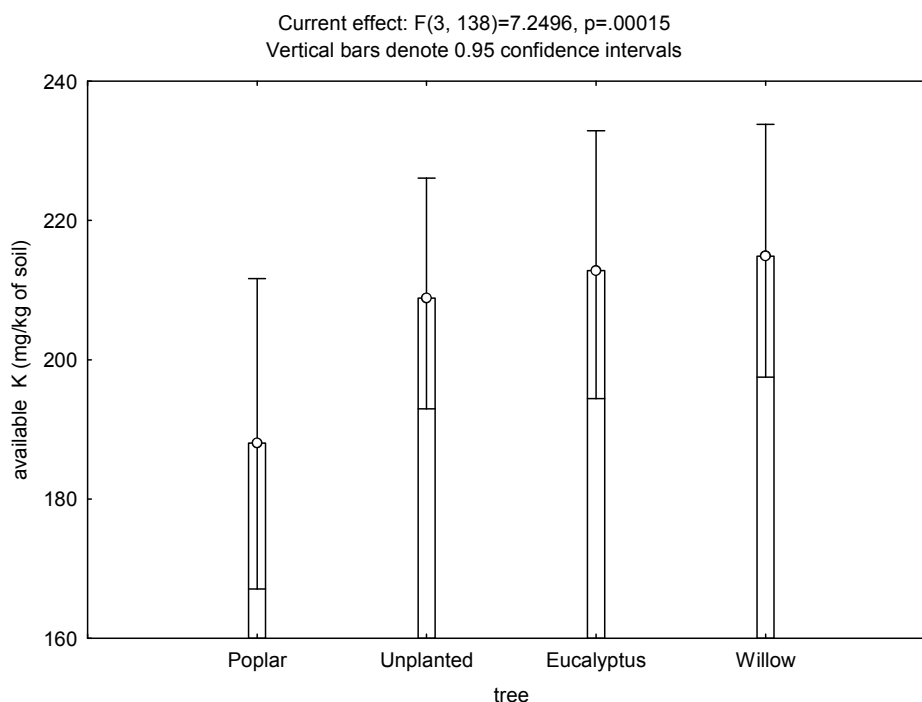


Figure 31 plot of mean available K grouped by cover for all depth, year and irrigated or not. Vertical bars denote 0.95 confidence interval.

Available K distributions were significantly affected by depth (Table 12). According to Chapter 3 (Section 2.3.3) the initial distribution of available K in the soil was not significantly heterogeneous, with a progressive increase of available K from surface until 100 cm and then a progressive decrease.

However, at the end of the 2 years of irrigation, the mean distribution of available K has changed, showing a progressive decrease from the surface to 50 cm depth. (Table 13). The enrichment of the profile in available K happened mainly in the first 10 cm more marked under irrigation but not significantly. The evolution of available K at 10cm under non-irrigated condition was the same under the different covers, there was a general enrichment. However, at 10 cm, under irrigated condition, for unplanted and willow, there was a decrease between 2007 and 2008. And a general reduction at all depth under unplanted-irrigated covers between 2007 and 2008 (there was a general enrichment at all depth between 2006 and 2007). The effect of irrigation and trees are more pronounced at 30 cm depth. Available K concentrations were homogenised, and especially under eucalyptus and willow. This was expected because 30 cm corresponds to the general maximum density root zone depth for all the trees studied (Trindade et al., 1997, Spangenberg and Kolling, 2004, Vos and van der Putten, P.E.L., September 2004)

Table 13 Mean available K (mg/kg of soil) grouped by depth in February 2008.

Depth	Mean available K (mg/kg of soil)	N
10 cm	254±84	70
30 cm	205±60	70
50 cm	195±61	70

This enrichment was not dependant on irrigation even though irrigated plots presented higher available K concentrations than the non-irrigated ones ($P>0.05$).

There was a progressive enrichment of the profile with time from 2006 to 2008 (the mean available K concentration rose from 158.6 mg.kg^{-1} of soil in 2006 to $271.39 \text{ mg.kg}^{-1}$ of soil in 2008. (Figure 32).

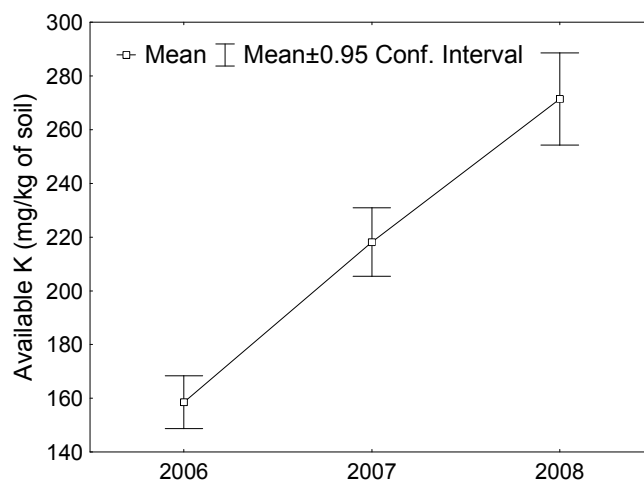


Figure 32 Mean plot of available K (mg.kg^{-1} of soil) grouped by year. Vertical bars denote 0.95 confidence interval.

There was no significant effect of irrigation on available K concentration in soil and no plant effect neither (as the poplar effect results more on the initial heterogeneity of available K distribution within the field as in February 2006, when samples were taken, there wasn't any tree grown nor irrigation performed). However, there was a general enrichment at all depths of available K with time resulting from soils natural evolution.

To determine from where this potassium came, as it was not coming from irrigation, the evolution of total potassium, TK, is discussed in the following section.

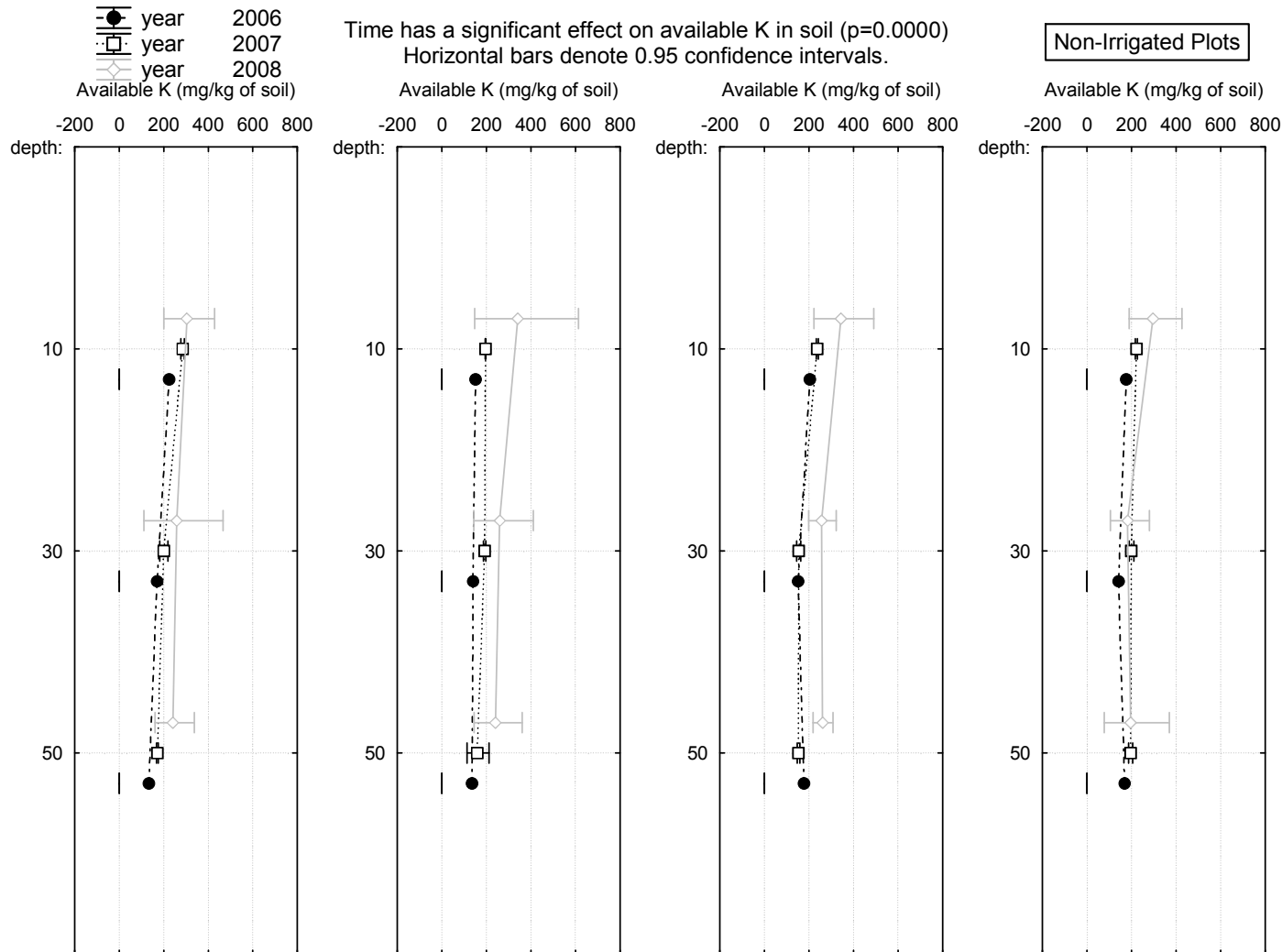


Figure 33 Available Potassium evolution in soil at 3 depths (10, 30 and 50cm), under 4covers (unplanted, eucalyptus, poplar and willow) non irrigated from February 2006, 2007 and 2008. Graphs were staggered at each depth for clarity.

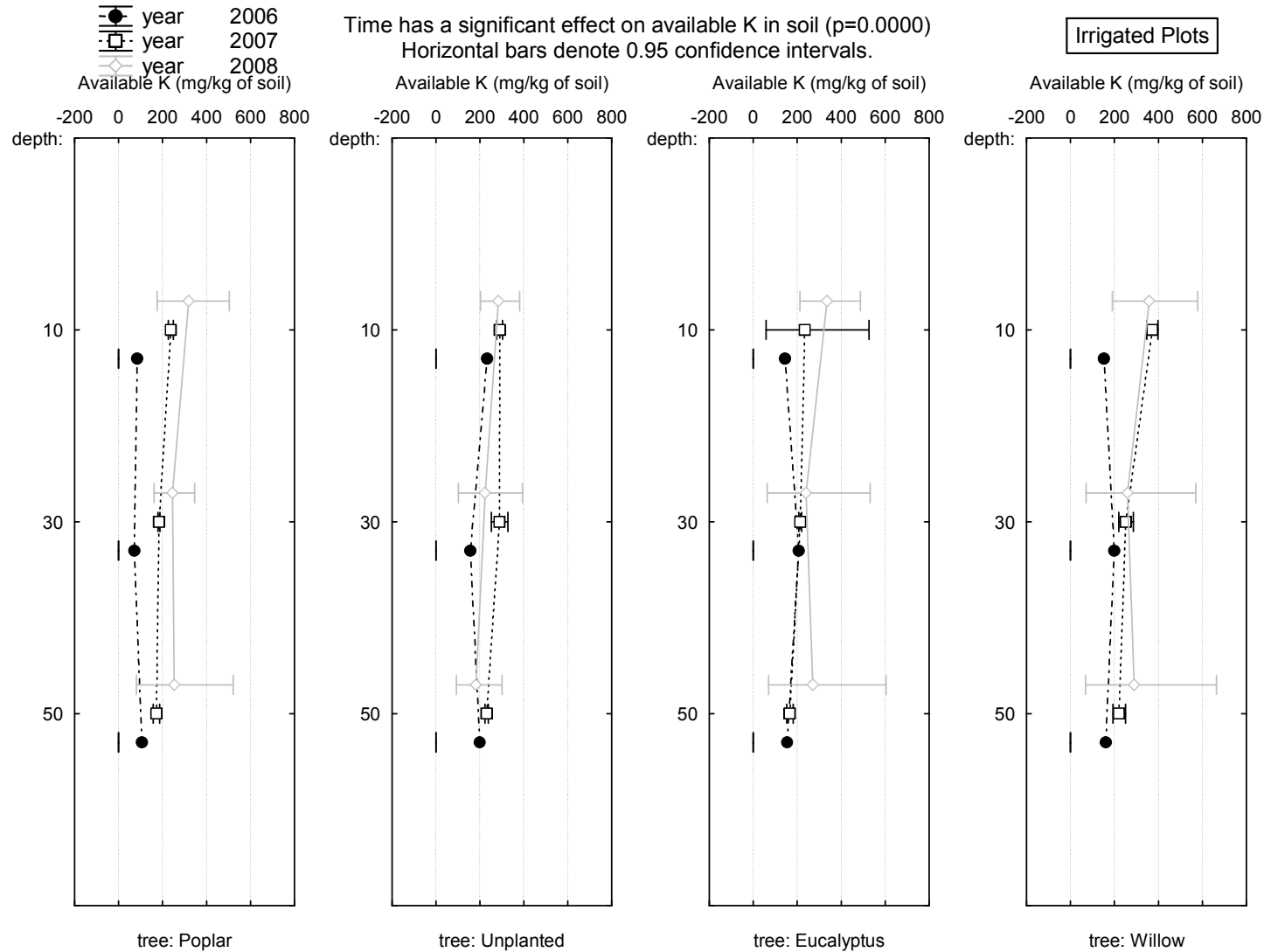


Figure 34
Available Potassium evolution in soil at 3 depths (10, 30 and 50cm), under 4 covers (unplanted, eucalyptus, poplar and willow) irrigated from February 2006, 2007 and 2008. Graphs were drawn staggered at each depth for clarity.

3.10.2 Total Potassium

ANOVA on TK concentrations in soil revealed that none of the factor considered had a significant effect (Table 14).

Table 14 ANOVA table on TK concentration of soil samples taken at 3 depths on each plot in February 2006, 2007 and 2008.

	Degree. of - Freedom	TK g/kg of soil - F	TK g/kg of soil - p
Intercept	1	2341.82	0.000
cover	3	0.55	0.650
irrigation	1	1.28	0.263
depth(cover*irrigation)	16	0.45	0.964
year(cover*irrigation*depth)	48	1.15	0.298
cover*irrigation	3	1.64	0.188
Error	72		
Total	143		

As the amount of K added or uptaken were the order of 100 mg.kg^{-1} of soil and the average TK concentration in soil was $104 \pm 4 \text{ g.kg}^{-1}$ of soil (Figure 35), they represented less than 0.1 % of TK. TK soil pool is massive in soil therefore, no significant effect of nor tree presence, nor irrigation was to be expected.

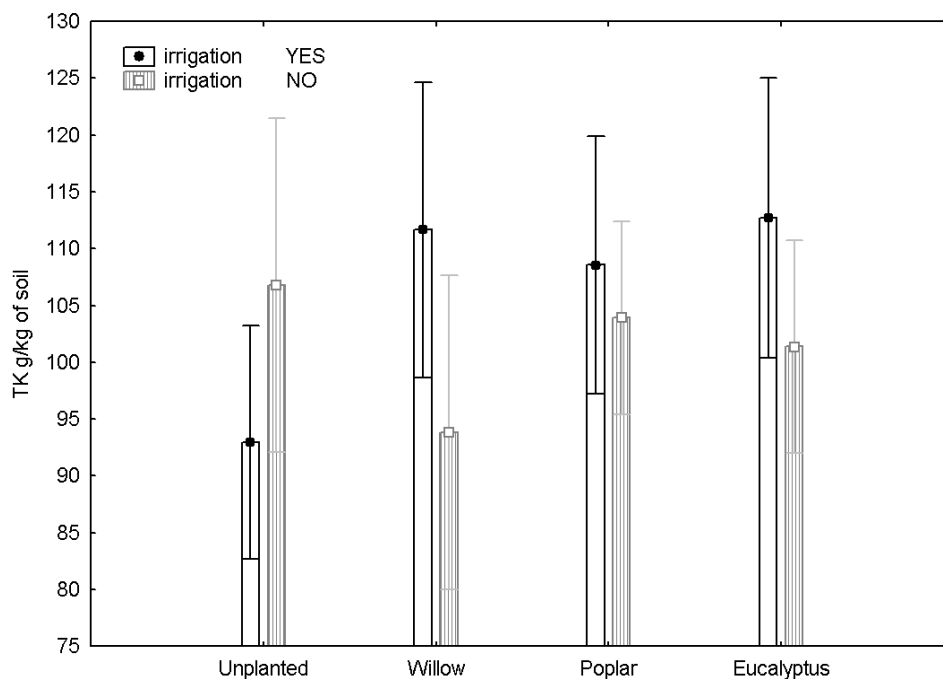


Figure 35 Total Potassium averaged by covers (unplanted, eucalyptus, poplar and willow) and irrigation from samples collected in February 2006, 2007 and 2008. Vertical bars denote 0.95 confidence interval.

The enrichment in available K of soil profile was around 50 mg.kg^{-1} of soil, therefore around 0.05 % of the average TK concentration in soil. Such amounts of variation would have been detected with the precision of the method used but these increased concentrations can be explained by natural K leaching resulting from clay weathering (Ferguson and De Groot, 2000).

4. CONCLUSION

The specific objectives of this soil analysis chapter were to:

- **Objective 1:** Identify and quantify significant changes in soil chemistry as a result of effluent tertiary treatment, i.e. N and P removal. (K removal will be considered as well as essential macronutrient for plant growth).

The implementation of a WaterRenew system (irrigation and tree growth) did not have any significant effect on N and P in soil. Even after pushing the system by high effluent application rate (30 mm.day^{-1} for 10 days), there was no significant effect. Indeed, the amounts of nutrients applied were low compared to the existing soil pool. TN applied by irrigation corresponded to 2-6 % of TN present in soil and the amount of TN uptaken to 0.4-1.5 %. Therefore, the absence of irrigation and tree effect would be expected.

For P, the amount applied corresponded to 30-60 % of initial Olsen-P in soil and the amount uptaken less than 40 % of the amount applied; hence, an irrigation effect with an accumulation was expected on Olsen-P but was not observed in the data. This decrease in Olsen-P underlines clay important P sorption capacity. Initially, Olsen-P corresponded to less than 15 % of TP in soil.

For K, the amount applied represented from 16-26 % of extractable K present in soil initially. The amounts uptaken ranged from 4.3-18 % of extractable K value, therefore, no significant effect of WaterRenew system implementation was expected (extractable K representing less than 10 % of TK in soil).

Therefore, Cranfield site WaterRenew system did not reach its soil organic and inorganic limits to retain and transform nutrients and revealed, prior to soil water analysis, a great potential to remove N and P from effluent.

- **Objective 2:** Identify and quantify possible adverse effect, significant or not on soil chemistry results of a water renew system; in particular P accumulation and salinisation. And understand the processes involved.

After having monitored soil SAR, EC, pH and nutrients content (TON, Ammonium, TN, Olsen P, TP, available K, TK, Na), the impact of the installation of WaterRenew system was significant only for SAR and Na extracted in both saturated paste and ammonium nitrate. Indeed, irrigation increased their values significantly however soils remained neither saline nor alkaline. As the amount of Na applied by irrigation corresponded to over 340 % of extractable Na values initially present in soil in 2006 and over 580 % of extractable Na values in soil in 2007, this significant impact of irrigation on Na in soil was expected.

For P, P sorption finite capacity was identified as a potentially limiting factor for a WaterRenew system in Chapter 2. The only statement that could be made was that P sorption capacity had not been reached during this experiment and further experiments are necessary to conclude on the system sustainability regarding P.

Thus, on the wastewater treatment side, the WaterRenew system implemented on a chalky clayey soil, was not impacting significantly the soil on the nutrient point of view, however, there was an enhanced acidification and salinisation of the soil due to irrigation, although those phenomena were also happening even without irrigation.

The presence of tree had a smaller impact on the different variables monitored than irrigation.

Hence, for Cranfield soil and climate conditions, a WaterRenew system was impacting significantly the soil by a statistical significant acidification but not a significant change in soil quality by salinisation yet. Indeed, Na accumulation, although still small, is an important concern and should be kept being monitored in future sites.

5. REFERENCES

- Allen, R. G. (1998.), *Crop evapotranspiration : guidelines for computing crop water requirements*, Food and Agriculture Organization of the United Nations, Rome.
- Armstrong, A., Great Britain., F. C. and Willoughby, I. (2002.), *Establishment and management of short rotation coppice*, Forestry Commission, Edinburgh.
- Aronsson, P. and Perttu, K. (2001), "Willow vegetation filters for wastewater treatment and soil remediation combined with biomass production.", *Forestry Chronicle*, vol. 77, no. 2, pp. 293-299.
- Behboudian, M. H., Pickering, A. H. and Dayan, E. (2003), "NUTRITION | Deficiency Diseases, Principles", in Brian Thomas (ed.) *Encyclopedia of Applied Plant Sciences*, Elsevier, Oxford, pp. 642-649.
- Bender, M. R. and Wood, C. W. (2000), "Total Phosphorous in Soil.", *Methods for P Analysis, G.M. Pierzynski (ed), Southern Cooperative Series Bulletin*, vol. 396, pp. 45-49.

- Brookes, P. C., Heckrath, G., De Smet, J., Hofman, G. and Vanderdeelen, J. (1997), "Losses of Phosphorus in Drainage Water", in Tunney, H., Carton, O. T., Brookes, P. C., et al (eds.) *Phosphorus Loss from Soil to Water*, CAB international, UK, pp. 253-263.
- Conrad, R., Seiler, W. and Bunse, G. (1983), "Factors influencing the loss of fertilizer nitrogen into the atmosphere as N₂O.", *J. Geophys. Res.*, vol. 88, pp. 6709-6718.
- DEFRA (2002.), *Sewage treatment in the UK : UK implementation of the EC Urban Waste Water Treatment Directive : sensitive areas : September 2002*, Department for Environment, Food & Rural Affairs, London.
- DEFRA (2002), "Guidelines for Farmers in NVZs – England.", vol. PB5505.
- FAO (1985), *Guidelines: Land Evaluation for Irrigated Agriculture*. 55, FAO Soils Bulletin, FAO, Rome.
- Ferguson, R. B. and De Groot, K. M. (2000), "Nutrient management for agronomic crops in Nebraska.", *University of Nebraska*, .
- GB, Parliament. Joint Committee on Statutory Instruments. (2008), *The nitrate pollution prevention regulations 2008.(SI 2008/2349)*, The Stationery Office.
- Heckrath, G., Brookes, P. C., Poulton, P. R. and Goulding, K. W. T. (1995), "Phosphorus Leaching from Soils Containing Different Phosphorus Concentrations in the Broadbalk Experiment", *Journal of Environmental Quality*, vol. 24, no. 5, pp. 904-910.
- Lockwood, P. V., Daniel, H. and Wilson, B. R. (July 2004), "Soil acidification in relation to salinisation and natural resource management.", vol. 13th International Soil Conservation Organisation Conference, no. Conserving Soil and Water for Society: Sharing Solutions.
- MAFF, (2000), *Fertiliser recommendations for agricultural and horticultural crops (RB209)*, Seventh edition ed., the stationary office, London, UK.
- MAFF (1986.), *The analysis of agricultural materials: a manual of the analytical methods used by the Agricultural Development and Advisory Service*, 3rd ed, HMSO, London.
- MAFF (1986), "Changes in ADAS lime recommendations. Technical Bulletin SS/R/86/8", *Internal Publication*, .
- Mamo, M., Gupta, S. C., Rosen, C. J. and Singh, U. B. (2005), "Phosphorus leaching at cold temperatures as affected by wastewater application and soil phosphorus levels", *Journal of Environmental Quality*, vol. 34, no. 4, pp. 1243-1250.
- McGechan, M. B. (2002/6), "SW--Soil and Water: Sorption of Phosphorus by Soil, Part 2: Measurement Methods, Results and Model Parameter Values", *Biosystems Engineering*, vol. 82, no. 2, pp. 115-130.
- McGechan, M. B. and Lewis, D. R. (2002/5), "SW--Soil and Water: Sorption of Phosphorus by Soil, Part 1: Principles, Equations and Models", *Biosystems Engineering*, vol. 82, no. 1, pp. 1-24.
- NSRI (2008), "Soils site report (Full soil report)".
- Nutrient Manager (1996), "Focus on pH and lime.", *Nutrient Manager*, vol. 3, no. 2.
- Olsen, S. R., Cole, C. V., Watanabe, F. S. and Dean, L. A. (1954.), "*Estimation of available phosphorus in soils by extraction with sodium bicarbonate*.", *USDA*, vol. Circular 93., pp. 1-19.

- Pierzynski, G. M. (2000), "*Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters*", *Southern Cooperative Series Bulletin*, vol. 396, pp. 102.
- Pulleman, M. M., Bouma, J., van Essen, E. A. and Meijles, E. W. (2000), "Soil Organic Matter Content as a Function of Different Land Use History", *Soil Sci Soc Am J*, vol. 64, no. 2, pp. 689-693.
- Richards, L. A. and Allison, L. E. (1954.), *Diagnosis and improvement of saline and alkali soils*, U.S. Government Printing Office, Washington, D.C.
- Rowell, D. L. (1994), *Soil science : methods and applications*, Longman Scientific & Technical, Harlow.
- Sharpley, A. N., Curtin, D. and Syers, J. K. (1988), "Changes in Water-extractability of Soil Inorganic Phosphate Induced by Sodium Saturation", *Soil Science Society of America Journal*, vol. 52, no. 3, pp. 637-640.
- Sharpley, A. N. (1995), "Dependence of Runoff Phosphorus on Extractable Soil Phosphorus", *Journal of Environmental Quality*, vol. 24, no. 5, pp. 920-926.
- Soil Survey of England and Wales, (1993), *Legend for the 1:250,000 Soil Map of England and Wales*, Soil Survey, Harpenden, UK.
- Sumner, M. E. (1993), "Sodic soils: New perspectives.", *Australian Journal of Soil Research*, vol. 31, no. 6, pp. 683-750.
- Syers, J. K., Williams, J. D. H., Campbel, A. S. and Walker , T. W. (1967), "The significance of apatite inclusions in soil phosphorous studies.", *Soil Sci. Soc. Amer. Proc.*, vol. 31, pp. 752-756.
- Szabolcs, I. (1989), "Amelioration of soils in salt affected areas", *Soil Technology*, vol. 2, no. 4, pp. 331-344.
- Tisdale, S. L., Halvin, J. L., Beaton, J. D. and Nelson, W. L. (1999), "Soil fertility and fertilizers: an introduction to nutrient management.", *6 th Edition*, .
- USGS (September 1999), "Environmental Characteristics of Clays and Clay Mineral Deposits", *USGS Information Handout*, .
- Westcot, D. W. (1988), "Reuse and disposal of higher salinity subsurface drainage water — A review", *Agricultural Water Management*, vol. 14, no. 1-4, pp. 483-511.
- Westcot, D. W., Food and Agriculture Organization of the United Nations. and Ayers, R. S. (1985.), *Water quality for agriculture*, Food and Agriculture Organization of the United Nations, Rome.

CHAPTER 6: EVOLUTION OF SOIL WATER AND GROUNDWATER CHEMISTRY ON PLANTED PLOTS IRRIGATED WITH SECONDARY TREATED EFFLUENT

1. INTRODUCTION

A WaterRenew system is defined as a system where wastewater is irrigated onto fast-growing tree species with a double objective; first, wastewater polishing and second, fertigation of the trees with subsequent the aim of boosting yield. Responses of a SRC to irrigation with wastewater under UK specific edapho-climatic conditions have not yet been studied. Therefore, a small scale ($24 \times 12.25 \text{ m}^2$), short rotation coppice (SRC¹) was irrigated with secondary treated effluent at the Cranfield University (Bedfordshire, UK) sewage treatment works, on a chalky clayey soil. The way the nutrients, applied by irrigation, travelled within the different compartments (plant, soil matrix and soil water) constituting the WaterRenew system was monitored and discussed in previous chapters.

Scott et al (2000) identified leaching of nutrients and/or other organic components into ground water as one of the main risks associated with wastewater irrigation of crops. These contaminations are important to take into account as they can compromise heavily surface and groundwater quality by eutrophication and nitrate pollution (DEFRA, 2002, Scott et al., 2000).

Studies have been conducted on the fate of N and N leaching in willow planted systems in Sweden (Aronsson and Bergstrom, 2001; Dimitriou and Aronsson, 2004) and eucalyptus plantation (Smith et al., 1999). Aronsson et al. (2000) and Dimitriou and Aronsson (2004) showed that a great amount of N could be “treated” or retained in soil-willow systems; in Sweden up to $200 \text{ kg-N.ha}^{-1}.\text{yr}^{-1}$ was applied and N-leaching as $\text{NO}_3\text{-N}$ concentration in groundwater was kept under 10 mg-N.L^{-1} , under the drinking water consent (EC, 2000.) .

Unlike N, P leaching from this kind of system has been studied less despite being recognised to be an environmental threat (Cortina et al., 1995). The removal of P by soil-plant system was established by (Braskerud, 2002). In effect, P retention is imputable to soil particles (suspended or sediment) rather than plant (Braskerud, 2002;

Djodjic et al., 2004). In particular high levels of organic matter and high clay content were found to increase P retention (Harris et al., 1996) in such system.

Hence, in this context, the behaviour and efficiency of N and P retention, removal and treatment in the WaterRenew system installed at Cranfield University site (Bedfordshire, UK) were assessed.

Previously three key themes were discussed firstly; performances of three SRC species, *E. gunnii*, *S. viminalis* and *P. trichocarpa* in terms of water uptake, nutrient uptake and yield production were measured and described. Chapter 4 revealed that irrigation had a significant, positive effect on tree growth and tree yield for the three species studied.

Secondly, soil samples collected at 10 cm, 30 cm and 50 cm in February 2006, 2007 and 2008 and analysed for nutrients content and evolution (Chapter 5). The WaterRenew system did not change significantly the N, P and K soil pool. But there was a slight but statistically significant acidification and salinisation because of irrigation. The presence or absence of a tree had a little impact on soil chemistry.

Thirdly, to understand the fate of N and P in soil water, soil water chemistry under the three different tree species both irrigated or not; were monitored fortnightly through groundwater chemistry samples collected upstream and downstream the field.

The chapter is divided into three main parts: methodology, results and discussion and conclusion.

In particular, this chapter will address the statistical analysis results and discussion for ammonia, NH_4 (mg-N.L^{-1}), total oxidised nitrogen, TON (mg-N.L^{-1}), TN (mg-N.L^{-1}), phosphate, PO_4 (mg-P.L^{-1}), total phosphate, TP (mg-P.L^{-1}), potassium, K (mg-K.L^{-1}), sodium, Na (mg-Na.L^{-1}), pH and electrical conductivity, EC (dS.m^{-1}). Due to the soil water sampling method it is also possible to assess:

- **Objective 1:** identify and quantify significant changes in soil water and groundwater chemistry as a result of effluent tertiary treatment, i.e. N and P removal, and effectiveness.

¹ SRC: "coppice densely planted, high-yielding varieties of either willow or poplar, harvested on a 2 –5 year cycle, although commonly every 3years" (DEFRA, 2002.a).

- **Objective 2:** assess the relative importance of soil and trees on soil water chemistry changes, i.e. their relative importance in the effectiveness of a WaterRenew system as a wastewater tertiary treatment.

2. MATERIAL AND METHODS

2.1 SITE

A WaterRenew system was set up at Cranfield University sewage treatment works (Bedfordshire, UK) in October 2005. The mean annual precipitation is 629 mm; 10.0°C mean annual temperature and an annual average Penman evapotranspiration of 1.4 mm.day⁻¹ (Cranfield University, Silsoe met station, data from 1962-2006).

According to Soil Survey of England and Wales soil map (1993), Cranfield site soil is a Pelosol, a slowly permeable clayey soil or Hanslope, a chalky clayey soil (NSRI, 2008).

2.2 TREATMENTS

The field was artificially built and the soil completely disturbed. It was divided into 24 plots of 3.5 m by 3.5 m spaced with a 1 m pathway (Figure 1). Each plot was bounded by a polythene sheet of 60 cm width buried to 50 cm depth to prevent surface runoff or near surface lateral movement. The 24 plots were organised in three replicates randomly distributed, of four covers under two treatments. The covers were: 16 trees of willow (W, *Salix viminalis*), poplar (P, *Populus trichocarpa*), eucalyptus (E, *Eucalyptus gunnii*) at a tree spacing of 1 m, the four inner trees being measurement trees, and an unplanted control, (U). The plots were randomly assigned to be either: irrigated with wastewater (+) or non-irrigated (-) as a control of treatment. Usually, at the end of the first year, mono-stems are cut back to promote sprouting (DEFRA, 2002.a). In order to mimic this second year cut back poplars and willows were planted as a cluster of five cuttings in spring 2006.

A computerised drip-irrigation system was set up, with 16 drippers (4 L.hour⁻¹) per plot from July 2006 until August 2007. Then, in August 2007, the irrigative capacity was doubled from 15 mm.day⁻¹ to 30 mm.day⁻¹ on installing new drippers. The effluent irrigated was a secondary treated effluent pumped at Cranfield University sewage treatment work.

The main idea of the irrigation system settings was to allow the maximum water application whilst avoiding runoff, minimising drainage and consequently creating well

watered favourable conditions for plant growth. For this reason, the irrigation was triggered by soil moisture measurements (soil moisture sensor SM200, Delta T) in the middle of each plot to start when soil moisture content is lower than field capacity. The irrigation started in mid-July 2006 and continued until late December 2006. Then, it was stopped due to water freezing in the pipe work until late February 2007. The second irrigation period lasted from March 2007 until October 2007 but manual doses of effluent were added during winter 2007-2008 until February 2008 when the trees were harvested.

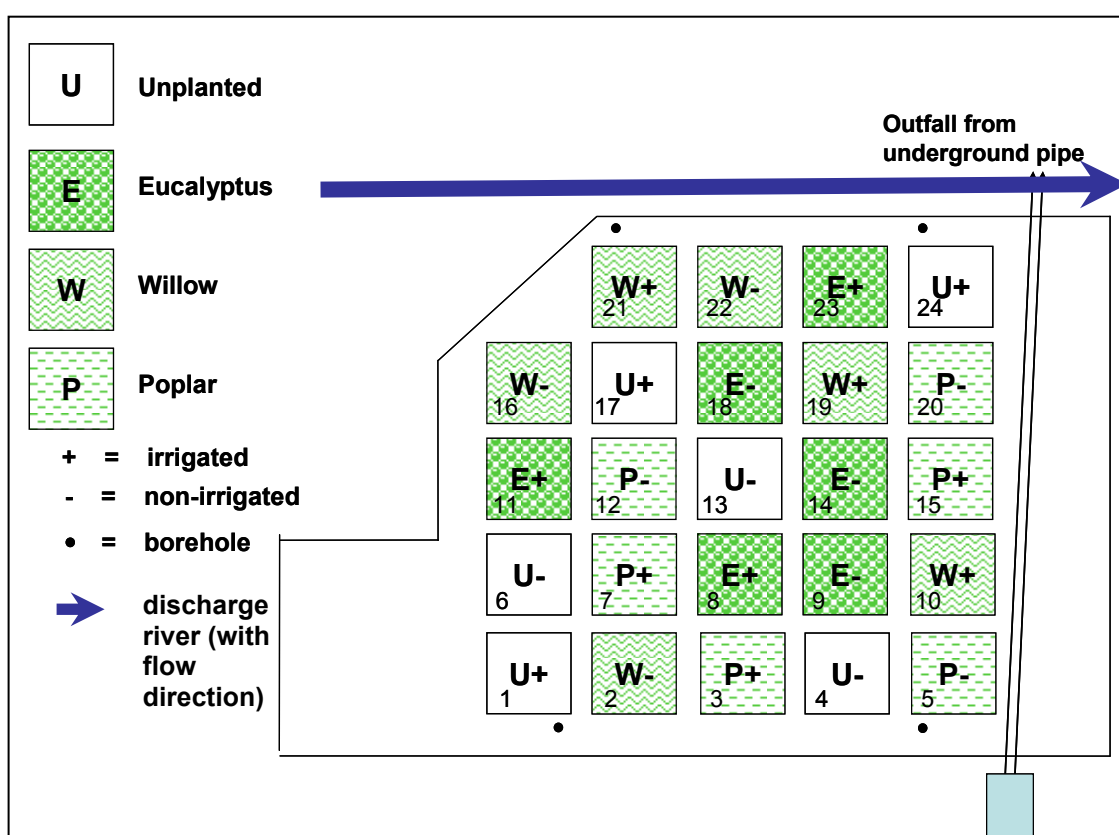


Figure 1 Cranfield site field trial map, localisation of 24 randomly distributed plots, 3 replicates of 4 covers, unplanted, eucalyptus, willow and poplar, irrigated or not.

2.3 SAMPLING OF IRRIGATION WATER, SOIL WATER AND GROUNDWATER

Effluent, soil water and groundwater samples were collected jointly, fortnightly, and throughout the year from the 22/07/06 until the 11/02/08 with a complementary

additional sampling on the 18/05/08, three months after the experiment was terminated in February 2008 by tree harvest.

The effluent used for irrigation is a secondary treated effluent from the Cranfield University sewage treatment works (STW). This effluent meets UK regulations in term of discharge quality. Its analysis according to FAO 29 (1985) classifies its use restriction for irrigation as none to slight.

The STW has a design capacity of 2,000 p.e² and effluent was collected directly from the final discharge tank. Samples of effluent were collected directly from the discharge tank and analysed without filtration.

Soil water was sampled by applying -60 kPa to soil water suction cup samplers made in Teflon to prevent P adsorption on their surfaces. On each plot, two Prenart suction cup samplers were installed to reach soil water first at 30 cm (soil water in the root zone) and second at 60 cm depth (soil water leaving the system). As there was a perched water table around 80 cm depth in some plots, the bottom of the system was considered as being 60 cm depth.

Groundwater was sampled fortnightly with soil water, from the four 1.70 m deep dip wells. Samples were collected by siphoning a 10 mm diameter plastic tube of 1.50 m length.

All samples were stored at 5°C and analysed within 10 days of collection.

2.4 CHEMICAL ANALYSIS OF IRRIGATION WATER

The same analyses were conducted on all samples from all sources.

Ammonia concentrations (NH₄) were determined by the Bertholet reaction (Burkard scientific). Phosphate (PO₄) and total phosphorus (TP) concentrations were determined by the molybdate/ascorbic acid method (Burkard scientific). Total oxidised nitrogen (TON) and total nitrogen (TN) were determined by forming a red azo dye that may be measured at 520nm (Burkard scientific). Potassium, K, concentrations were measured by a flame photometer and pH and electrical conductivity (EC) are measured by Jenway 4400 pH and conductivity meter. (cf. Chapter 3, 6.1.1)

Then, to address salinisation risks, sodium absorption ratio (SAR) was measured on an effluent sample in June 2008.

² p.e.: population equivalent

2.5 STATISTICAL ANALYSIS

The significance of the possible effect of irrigation and cover type on soil water and groundwater chemistry was assessed using analysis of variance (ANOVA), with transformations to normalise data and equalise variance as required (McBean and Rovers, 1998). The general linear model option in STATISTICA 7 (StatSoft, Inc., 2005) was used for this analysis. The significance level was set at $p < 0.05$ and comparisons between means were made with the least significant difference test (Fisher-test). The factors considered in the linear model, for soil water chemistry, were the factor cover with four levels (willow, poplar, eucalyptus and unplanted), the factor irrigation with two levels (YES and NO), the factor depth (of sampling soil) with two levels (30 cm and 60 cm) and the factor date with 36 levels (fortnightly sampling from the 22/07/06 until the 11/02/08 with a complementary sampling on the 18/05/08). The factor considered in the linear model for groundwater chemistry was the factor date with 36 levels (fortnight sampling from the 22/07/06 until the 11/02/08 with a complementary sampling on the 18/05/08) (Cf. Chapter 3, 7).

3. RESULTS AND DISCUSSION

3.1 COMPOSITION OF THE EFFLUENT USED FOR IRRIGATION

The effluent used for irrigation is a secondary treated wastewater with the average composition presented in Table 1.

Table 1 Average composition of effluent used for irrigation. (Relative concentration in relation with N as TN=100, n/a; non applicable)

	<i>Mean</i>	<i>Standard deviation</i>	<i>If N=100 (N as TN)</i>
<i>N</i>	34	34	
<i>K (mg.L⁻¹)</i>	48	58.9	160
<i>Na (mg.L⁻¹)</i>	69.7	47.3	232
<i>pH</i>	7.2	0.5	n/a
<i>EC (dS/m)</i>	0.7	0.1	n/a
<i>Ammonia (mg-N.L⁻¹)</i>	0.5	0.9	2
<i>TON (mg-N.L⁻¹)</i>	24.7	6	82
<i>TN (mg-N.L⁻¹)</i>	30	9.6	100
<i>Phosphate (mg-P.L⁻¹)</i>	4.2	1.7	14
<i>TP (mg-P.L⁻¹)</i>	4.4	3.7	15

This average composition was calculated as a proportion of TN, with the TN concentration equalled to 100. These proportions were compared to average concentrations in raw wastewater and tertiary treated wastewater provided by (Aronsson and Perttu, 2001). Cranfield University sewage composition was very low in P (15 for N=100 < 60 for N=100 in average tertiary treated wastewater) but contained very high amounts of (160 for N=100 > 4.5 for N=100 in average tertiary treated wastewater). K pollution in surface water can be originated by wastewater as K is one of the principal salts used in detergents and softeners (Baert et al., April 22-26, 1996) or by agriculture as component of potassium nitrates or nitrites, N fertiliser (Isermann, 1994). However, K is not considered as a potential threat for human health or water quality and was withdrawn from the list of dangerous component of drinking water (EUREAU, 1993).

Table 2 Comparison of the relative concentrations of N, P, K in the different municipal wastes, optimum composition for SRWC, Eucalyptus and Poplar nutrients uptake in relation to N=100, adapted from Aronsson and Perttu 2001.

<i>Element</i>	<i>N</i>	<i>P</i>	<i>K</i>
Untreated wastewater	100	64	17.5
Tertiary treated wastewater	100	60	4.5
Average sludge in Sweden	100	9	73
Average landfill leachate in Sweden	100	54	0
Optimum composition for SRWC	100	72	14
Eucalyptus urophylla hybrids (Brazil 7yrs)	100	8	57
Populus trichocarpa	100	15	45

The different components of the effluent irrigated were analysed in soil water samples to investigate irrigation and plant effects on their concentrations at two depths, 30 and 60 cm.

3.2 PHOSPHATE AND TOTAL PHOSPHATE

3.2.1 Phosphate and total phosphate in soil water

In soil water, phosphate and total phosphate (TP) were detected only in few samples. Hence, when they were not detected, their concentrations were lower than 0.01 mg-P.L⁻¹ (the detection limit). Some measurements were higher than the limit of detection; however, they were not numerous enough (4.7 % of samples were presenting detectable concentrations) to run any ANOVA.

Table 3 Descriptive statistics on phosphate and TP data from irrigated and non-irrigated plots, at 2 depths (30 cm and 60 cm) and under all covers (unplanted, willow, poplar, eucalyptus).

	<i>Valid N</i>	<i>Mean</i>	<i>Minimum</i>	<i>Maximum</i>	<i>Maximum for</i>	<i>Standard Deviation.</i>
Irrigated plots: PO₄ (mg-P.L⁻¹)	686	0.01	0.00	1.30	Poplar, 60cm on the 05/10/07	0.08
Irrigated plots: TP (mg-P.L⁻¹)	697	0.04	0.00	8.28	Unplanted, 60 cm on the 16/01/07	0.39
Non-irrigated plots: PO₄ (mg-P.L⁻¹)	456	0.02	0.00	1.76	Willow, 60 cm , on the 23/01/08	0.12
Non-irrigated plots: TP (mg-P.L⁻¹)	472	0.07	0.00	7.80	Poplar, 30 cm, on the 01/02/07	0.51

There were fewer samples collected for non-irrigated plots (460 compared to 690), even though suction was applied for 24 hours at -60 kPa. This is because irrigation wetted the soil profile enabling soil water sampling whereas on the drier non-irrigated plots, it was not possible to collect enough samples for analysis and dilution would be too great to ensure sample representativeness.

For both phosphate and TP, averages were higher for non-irrigated plots than for irrigated plots. However for TP, the maximum concentration was measured on irrigated plots but this concentration was not significantly higher.

3.2.2 Phosphate and total phosphate in groundwater

For ANOVA to be applicable, residuals need to follow a normal distribution (McBean and Rovers, 1998) (details in Chapter 3, 4, 4.1.2). Hence, TP data had to be transformed to ensure residuals normal distribution. However, for PO₄ data it was not possible to find a transformation to ensure residuals normal distribution, hence only TP data are presented.

Table 4 ANOVA table for log(TP) from both upstream and downstream sampling (in bold, significant factors, $p < 0.05$)

	<i>Degree of Freedom</i>	<i>log(TP) - F</i>	<i>log(TP) - p</i>
Intercept	1	147.58	0.00
date(location)	6	46.55	0.00
location	1	37.93	0.00
Error	5		
Total	12		

Concerning WaterRenew system implementation, on Cranfield site, irrigation with secondary treated effluent of a short rotation coppice did not have any negative influence on groundwater TP concentrations.

Indeed, according to Table 4, the implementation of a WaterRenew system has a significant effect on TP concentration in groundwater however; the time of groundwater sampling also has a significant effect on TP concentration. Although, there were only 11 samples with TP concentrations above the limit of detection for upstream samples and only 2 samples with TP concentrations around the limit of detection for downstream samples. Hence, the effect of the site is more on lowering TP concentrations in groundwater downstream the site. For upstream samples, the greater values could not be linked to any of the flooding events of October 2006 or beginning of January 2007. On observing the data, TP concentrations were higher from autumn and winter, when rain was less abundant (Figure 2) and lower during summer when rainfall was more abundant. Hence, rainfall diluted TP in groundwater.

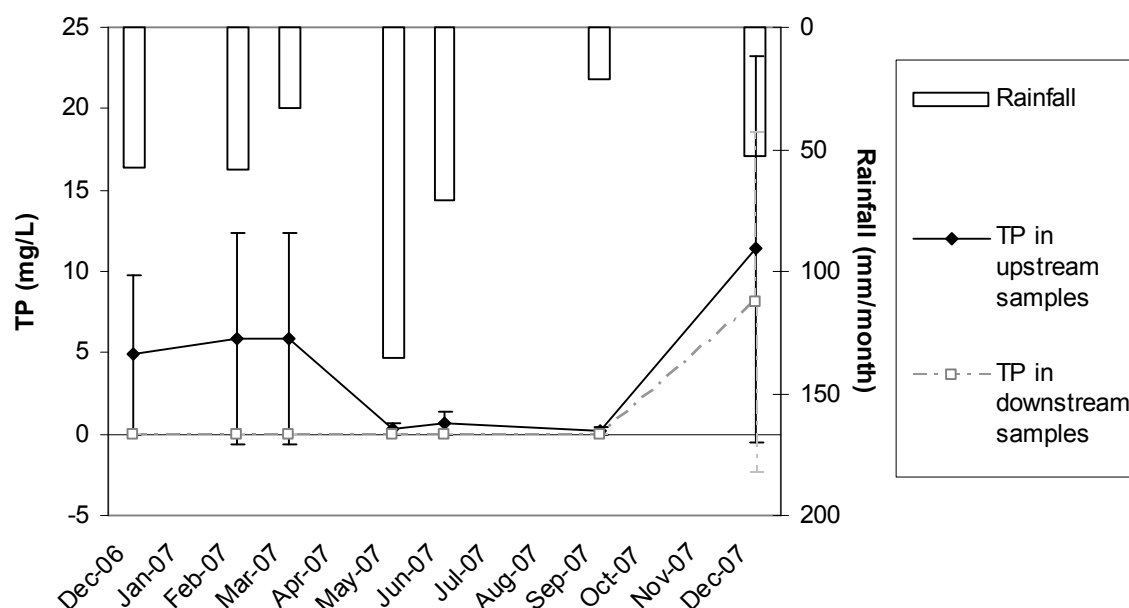


Figure 2 Evolution of TP concentrations on from upstream and downstream samples collected fortnightly from 28/10/06 until the 18/05/08. (vertical bars denote 0.95 confidence interval)

Therefore, the WaterRenew system implemented on Cranfield site, i.e. irrigation with secondary treated effluent of a short rotation coppice did not have any negative influence on groundwater TP concentrations.

As TP concentrations in soil water were under the limit of detection and TP in groundwater were presenting greater concentrations upstream than downstream the field, then, P applied by irrigation was effectively adsorbed onto soil particles or uptaken by tree roots.

Chapter 5, 4.8, revealed that Olsen-P increased at the surface (0-10 cm depth) of irrigated plots, which can corroborate effluent P adsorption theory.

3.3 NITROGEN IN SOIL WATER AND GROUNDWATER

3.3.1 Ammonia in soil water

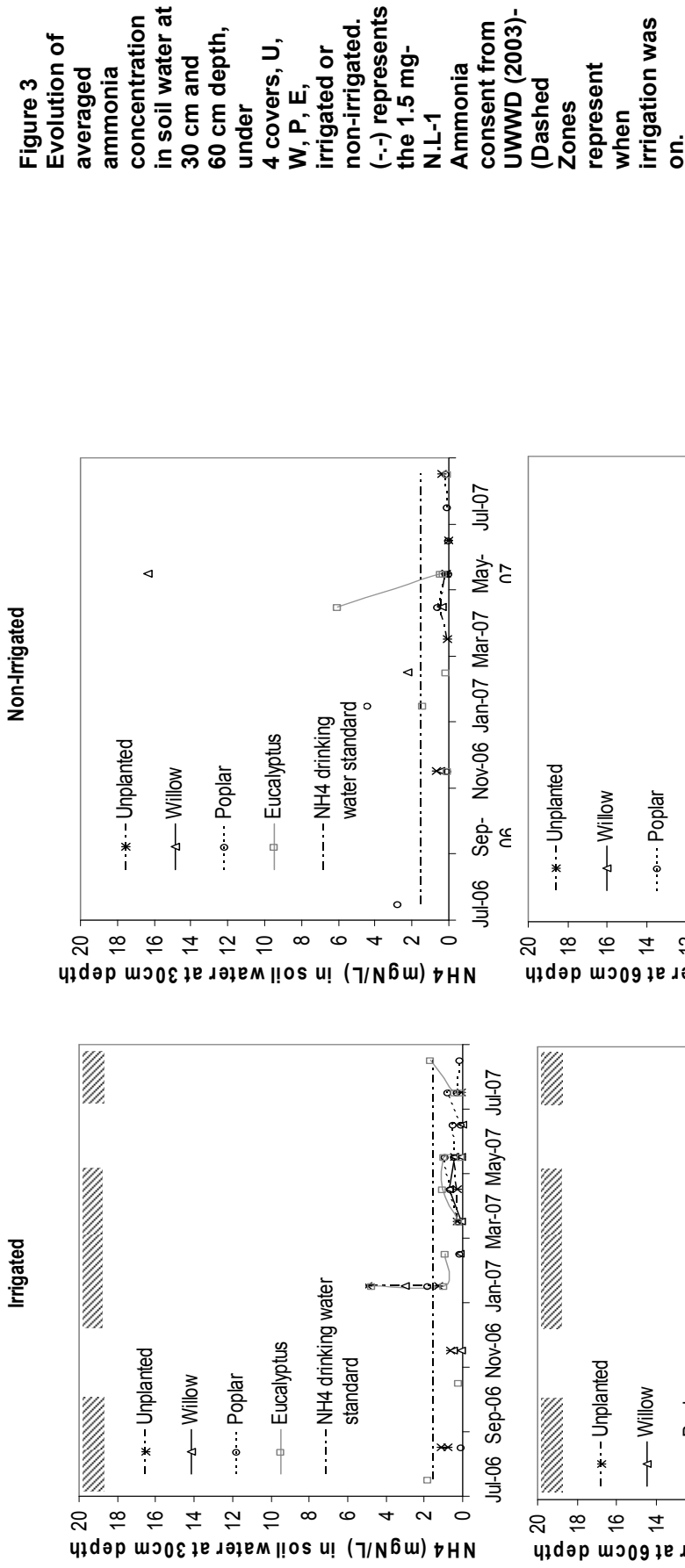
Ammonia data had to be transformed to ensure residuals normal distribution.

ANOVA concluded there was a significant effect of depth, date and the interaction of tree and irrigation on ammonia concentrations in soil water (Table 5).

Table 5 ANOVA table for $\log(\text{NH}_4)$ in soil water under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p < 0.05$)

	<i>Degree of Freedom</i>	<i>$\log(\text{NH}_4)$ - F</i>	<i>$\log(\text{NH}_4)$ - p</i>
Intercept	1	157.33	0.00
Cover	3	0.57	0.64
Irrigation	1	0.38	0.54
depth(cover*irrigation)	8	3.06	0.00
date(cover*irrigation*depth)	154	1.80	0.00
cover*irrigation	3	3.88	0.01
Error	102		
Total	271		

In particular, irrigation did not increase ammonia concentrations significantly in soil water but decreased it. Then, tree presence, inducing a greater NH_4 consumption or uptake, did not decrease significantly ammonia concentration in soil water (Figure 3).



Ammonia concentration in effluent was $0.5 \pm 0.9 \text{ mg-N.L}^{-1}$, hence always under the surface water discharge consent limit for the Cranfield sewage treatment works of 7 mg-N.L^{-1} (Official Journal (OL L 135, 30.05.1991, p.40) 1991; DEFRA, 2002.b).

The surface water discharge consent, used as a benchmark only, was exceeded for 3 soil water samples for irrigated plots and for 4 samples for non-irrigated samples at 60 cm depth. For irrigated plots, this occurred in March 2007 for unplanted, poplar and eucalyptus plots, shortly after irrigation was turned back on. After the winter break, at this period, the weather was already good (PSMD over 10 mm for 3 days before irrigation, Silsoe Met station) and soil relatively dry. At 30 cm depth for the 15/03/07, for all plots, ammonia concentrations were over the consent. The concentrations exceeding consent are almost 10 times greater than ammonia concentration in the effluent; around 5 mg-N.L^{-1} . Also, in March, soil microbiology and general biological activities were slowly starting again and ammonia resulting from winter mineralisation of organic N may have been available in soil (Rowell, 1994). Hence, the combination of a probable high ammonia content in soil and first application of effluent may explain this ammonia flush.

Moreover, ammonia concentrations were higher in samples from non-irrigated plots than irrigated ones. This confirms the possibility of an additional ammonia flush due to the water part of irrigation; the amount flushed exceeding the amount of ammonia added by the effluent. However, results from Chapter 5 (Chapter 5, 3.8.1, Figure 10) did not show an accumulation of ammonia in soil when sampled in February 2007. Hence, the peak of ammonia happening in March 2007 is probably triggered by irrigation onset, however, the height of the peak is difficult to explain.

Nevertheless, the main conclusion, from a treatment point of view, irrigation did not lead to higher ammonia concentration in soil water.

3.3.2 TON in soil water

Data were transformed to ensure residuals followed a normal distribution.

ANOVA concluded there were significant effects due to tree presence, depth and the interaction of tree and irrigation on TON concentrations in soil water (Table 6). In particular, TON concentrations did not vary significantly during the period of experiment when sampled at a same depth under the same cover, irrigated or not.

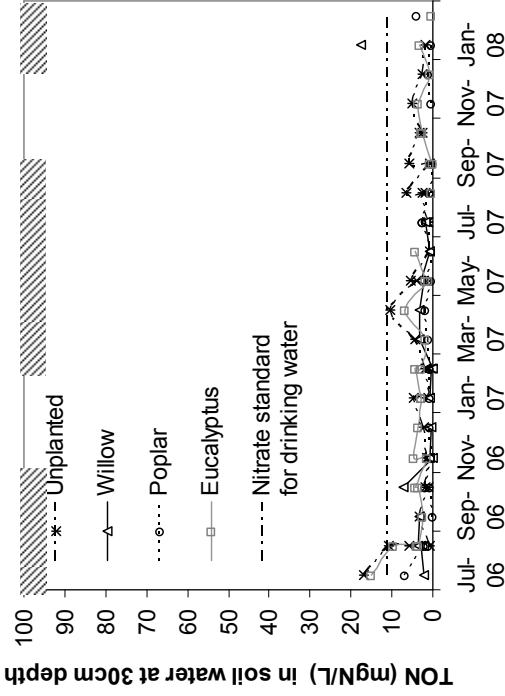
Table 6 ANOVA table for log(TON) under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p < 0.05$)

	<i>Degree of Freedom</i>	<i>log(TON) - F</i>	<i>log(TON) - p</i>
Intercept	1	1.41	0.24
Cover	3	7.03	0.00
Irrigation	1	0.64	0.42
depth(cover*irrigation)	8	3.95	0.00
date(cover*irrigation*depth)	406	1.11	0.15
Cover*irrigation	3	10.41	0.00
Error	1	450.20	0.00
Total	472		

Depth factor LSD (least significant difference) table analysis revealed that willow and poplar presence was; for all cases, lowering TON concentrations in soil water but for eucalyptus, it was increasing TON concentration in soil water sampled under irrigated plots at 30 cm and significantly in soil water sampled under non-irrigated plots at 60 cm (Figure 4).

The averaged TON concentration for 30 cm was greater than for 60 cm. The interaction between the cover factor and the irrigation factor was significantly impacting TON concentrations ($p < 0.05$ Table 6). However, according to the LSD table for this interaction factor, the significant differences in concentrations were for non-irrigated plot and planted with willow ($\text{TON}_{30\text{ cm}} < \text{TON}_{60\text{ cm}}$), eucalyptus and unplanted ($\text{TON}_{30\text{ cm}} > \text{TON}_{60\text{ cm}}$). Hence, the interaction factor had a significant effect on TON concentrations only under non-irrigated plots. Hence, irrigation homogenised TON concentrations between 30 cm and 60 cm. Because N mineralisation rate depends on organic matter content, it is expected to measure higher TON concentrations closer to surface than at depth (Nahm, 2005). Therefore, on unplanted non-irrigated plots, the measured TON distribution was the “undisturbed” distribution with higher TON content on the surface as there is more organic matter on surface (Brady and Weil, 2001). Irrigation redistributed this TON from superficial layer of soil, closer to surface and the location of more biological activity, to deeper soil layer with lower N content initially. Distributions of organic matter and N in soil by depth were presented in Chapter 5 (3.7 Organic matter and 3.8 Nitrogen in soil).

Irrigated



Non-Irrigated

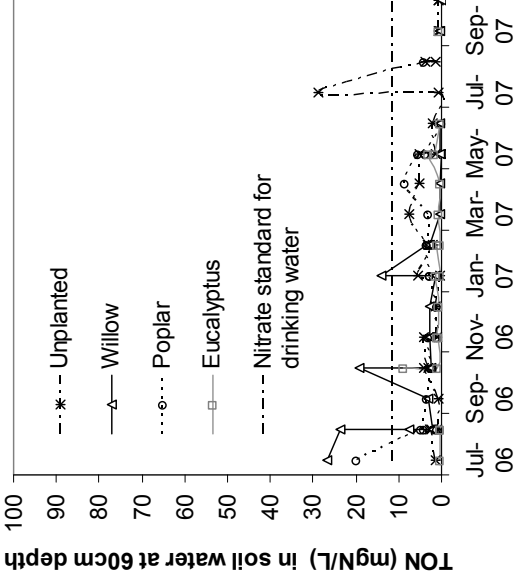
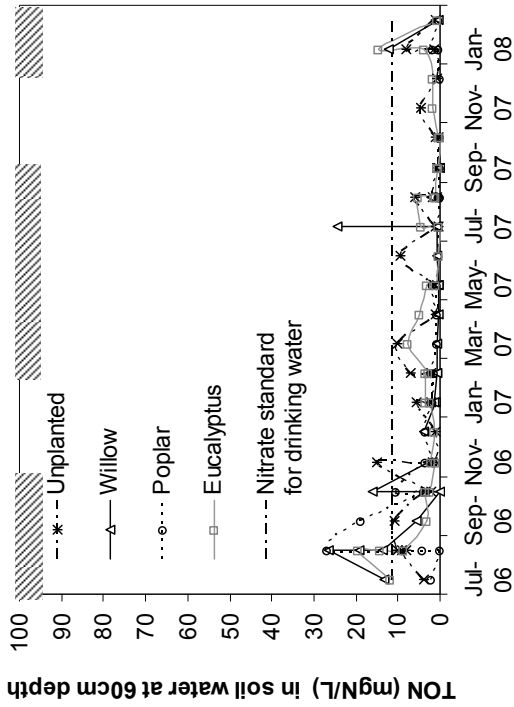
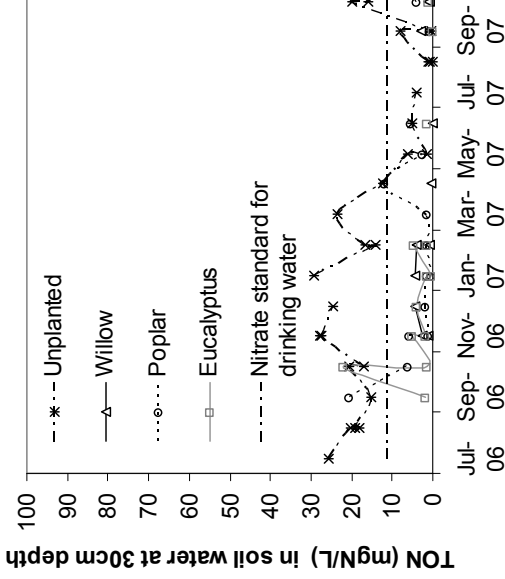


Figure 4 Evolution of averaged TON concentration at 30 cm and 60 cm depth, under 4 covers, U,W, P, E, irrigated or non-irrigated. (---) represents the 11.3 mg-N.L⁻¹ Nitrate standard from Drinking Water Directive (2003) (Dashed area for when irrigation was on)

All the mean values, average of the three replicates values for each cover and irrigation, are below 11.3 mg-N.L^{-1} (drinking water nitrate standard used as a benchmark). Moreover, all concentrations measured are lower than TON concentration in effluent. They represent around 10% of the application concentration ($\text{TON}_{\text{effluent}}$: $24.7 \pm 6.0 \text{ mg-N.L}^{-1}$).

TON and N in general can be in different forms in soil; in soil biomass (soil microbiology or root biomass), within soil matrix as mineral N or in solution in soil water (Rowell, 1994). As both nitrates and nitrites (both measured as TON) are anions, they were unaffected by the soils cation exchange process (Brady and Weil, 2001). Hence, TON applied may have been immobilised in organic-N, denitrified into N_2O or leached out in solution (Mengel, 1985). Concerning TON soil water concentrations evolution, results were presented in Figure 4. Even though not significant, TON concentrations in soil water showed some differences with time. The initial increase in TON concentration at the beginning of the experiment was in accordance with (Insam and Palojarvi, 1995) where both applications of slow or fast released N, P, K fertiliser induced TON and ammonia leaching into soil solution.

The standard value for nitrates in drinking water is 11.3 mg-N.L^{-1} and was used as a benchmark (DEFRA, 2002). However TON (nitrites + nitrates) were measured jointly, hence, this consent can be use as a benchmark only. For irrigated plots, at 30 cm, this benchmark was exceeded only 3 times by individual measurement on one replicate but was exceeded 23 times for non-irrigated plots. And for non-irrigated plots, it was mainly exceeded under unplanted plots. The concentrations were lower during summer 2007 when rainfall was greater. When it was raining less, it was much more difficult to get a sample and unplanted plots soil surface looked more cracked than planted plots. Hence, these forced extractions could explain those high TON concentrations under non-irrigated plots, as soil water was concentrated to be extracted. For 60 cm, TON concentrations exceeded the benchmark of 11.3 mg-N.L^{-1} 14 times and all at the during the first months of irrigation in 2006 for irrigated plots under all covers, but only 7 times for non-irrigated plots, first during the first month for willow and poplar planted plots and then, sporadically and without apparent relationship with any flooding or rainy episodes for willow, poplar and unplanted plots throughout the experiment. The fact there were higher concentrations of TON during the first months of irrigation is coherent with Aronsson findings (Aronsson and Bergstrom, 2001). Aronsson observed leached N was 187 % of the amount of applied N in year 1, 18 % and then 0.08 % for 2nd and 3rd

year when 220 kg-N.ha^{-1} was applied with irrigation of 640 mm (Aronsson and Bergstrom, 2001). Therefore, in Cranfield system, N leaching was not expected as there was no leaching happening under irrigated planted plots even though more than $794 \pm 288 \text{ kg-N.ha}^{-1}$ with $1247 \pm 700 \text{ mm}$ especially during the first year.

3.3.3 TN in soil water

Data were transformed to ensure residuals were normally distributed.

ANOVA concluded there was a significant effect due to tree presence, depth, date and the interaction of tree and irrigation on TN concentrations in soil water (Table 7). In particular, irrigation did not have a significant effect on TN concentrations.

Table 7 ANOVA table for log(TN) under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p < 0.05$)

	<i>Degree of Freedom</i>	<i>log(TN) - F</i>	<i>log(TN) - p</i>
Intercept	1	438.65	0.00
Cover	3	14.80	0.00
irrigation	1	0.08	0.78
depth(cover*irrigation)	8	4.94	0.00
date(cover*irrigation*depth)	455	1.43	0.00
cover*irrigation	3	11.17	0.00
Error	577		
Total	1047		

LSD table analysis revealed that at 30 cm, TN concentrations on average are greater than at 60 cm, and this difference is significant only under non-irrigated unplanted and eucalyptus plots. And irrigation has increased TN concentration at 30 cm compared to non-irrigated TN concentration at 30 cm only for eucalyptus whereas irrigation decreased TN concentration at 30 cm for all other covers. Effluent consists of a combination of water and nutrients, hence, this application of effluent can contribute to both, N leaching and N flushing by additional drainage. This is in accordance with the fact that the TN concentrations in samples under irrigation ($\text{TN}_{30\text{cm}} = 3.5 \pm 2.9 \text{ mg-N.L}^{-1}$ and $\text{TN}_{60\text{cm}} = 2.5 \pm 2.2 \text{ mg-N.L}^{-1}$) were significantly lower than in effluent ($\text{TN}_{\text{effluent}} = 30.0 \pm 9.6 \text{ mg-N.L}^{-1}$). TN evolution is consistent with TON evolution (Figure 4 and 5).

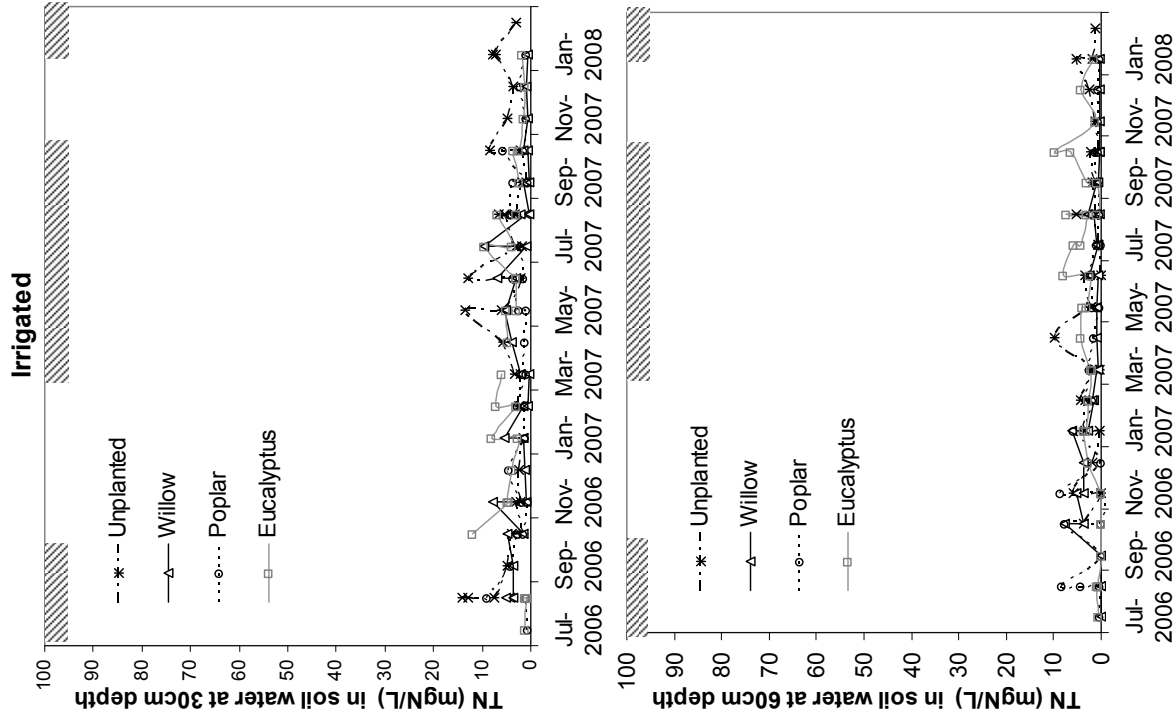


Figure 5
Evolution of
averaged TN
concentration
in soil water at
30 cm and
60 cm depth,
under
4 covers, U, W,
P, E, irrigated
or non-
irrigated
(Dashed zone
represent
when irrigation
was on)

On considering the actual values of these TN concentrations in soil water, the average was $TN_{\text{irrigated}} 6.95 \pm 12.27 \text{ mg-N.L}^{-1}$ for irrigated plots and $TN_{\text{non-irrigated}} 10.50 \pm 18.33 \text{ mg-N.L}^{-1}$ for non-irrigated plots. Moreover, TN concentration in effluent was $TN_{\text{effluent}} 30.0 \pm 9.6 \text{ mg-N.L}^{-1}$ (Table 1), hence, there is a reduction to a fifth between average TN concentration in effluent and average TN concentration in soil water under irrigated plots. This reduction might be due to a denitrification of this TN in solution or its assimilation into the organic matter pool.

LSD table analysis on date factor revealed that at the beginning of the experiment, for all plots, irrigated or not, TN concentrations in soil water were greater than for subsequent samples. TN concentrations in soil water during summer 2006 were significantly higher than for winter 2006-2007 for all plots but non-irrigated eucalyptus at 30 cm and unplanted plots at 60 cm where there was no significant variation on TN concentrations. (Figure 5)

To conclude on TN in soil water, first irrigation did not lead to an increase of TN in soil water and trees uptake led to a decrease, not significant, of TN in soil water. Therefore, this WaterRenew was efficient on removing TN brought by effluent irrigation.

3.3.4 Nitrogen in groundwater

3.3.4.1 Ammonia in groundwater

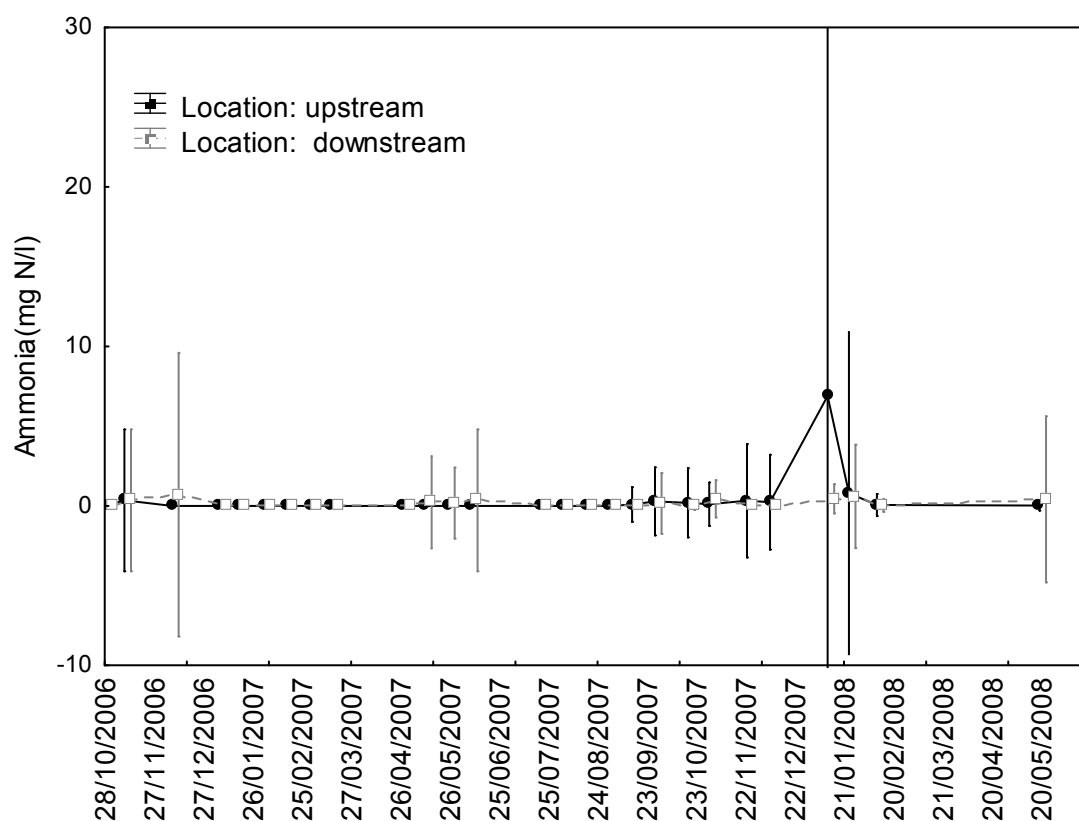


Figure 6 Evolution of ammonia in upstream and downstream groundwater samples from 28/10/06 until 19/05/08. (vertical bars denote 0.95 confidence interval)

ANOVA was not possible as there was not enough variability in the samples. However, the average for upstream samples was $0.35 \pm 1.32 \text{ mg-N.L}^{-1}$ but downstream samples average ammonia concentration was lower; $0.14 \pm 0.21 \text{ mg-N.L}^{-1}$. Hence, those averages are not significantly different. The same trend than for P was observed; the presence of the field seems to dilute ammonia concentrations in groundwater rather than concentrating it. Therefore, it is encouraging in terms of WaterRenew system efficiency.

3.3.4.2 TON in groundwater

TON data had to be transformed to ensure residuals normal distribution. (Table 8)

Table 8 ANOVA table for log(TON) from both upstream and downstream groundwater samples (in bold, significant factors, $p < 0.05$)

	<i>Degree of Freedom</i>	<i>log(TON) - F</i>	<i>log(TON) – p</i>
Intercept	1	0.20	0.66
date(location)	45	3.16	0.00
Location	1	13.82	0.00
Error	35		
Total	81		

Upstream samples TON concentrations were significantly greater than downstream TON concentrations; averages for upstream $0.96 \pm 0.72 \text{ mg-N.L}^{-1}$ and $2.17 \pm 2.97 \text{ mg-N.L}^{-1}$ for downstream. Soil water sampled at 60 cm from irrigated plots presented an average TON concentrations of $4.1 \pm 5.7 \text{ mg-N.L}^{-1}$ and an average of $3.5 \pm 5.6 \text{ mg-N.L}^{-1}$ for non-irrigated plots. Hence, it is possible that the presence of the WaterRenew system at Cranfield site increased significantly TON concentrations in groundwater but they remained well under the nitrate directive nitrate consent concentration of 11.3 mg-N.L^{-1} used here as a benchmark. However, it could be possible that downstream TON concentrations were greater because of exchange with river water. But river water TON concentration was not measured and the hypothesis there was no exchange between groundwater and river water could not be verified.

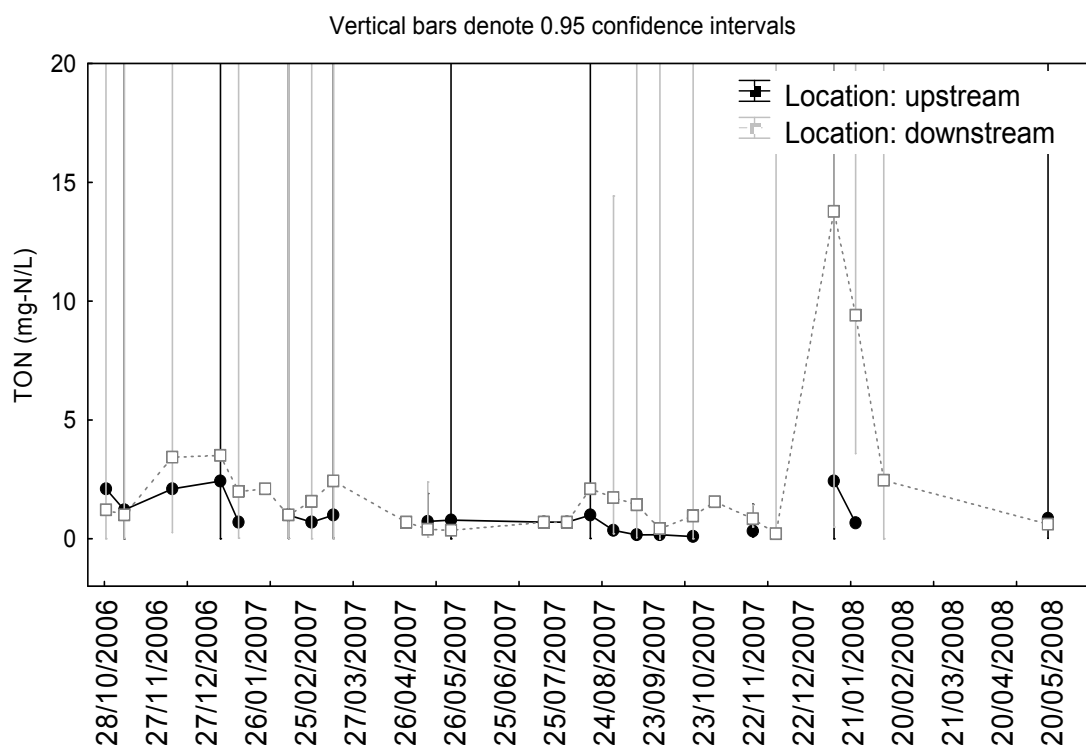


Figure 7 Evolution of TON in upstream and downstream samples from 28/10/06 until 19/05/08. (- -) 11.3 mg-N.L⁻¹ nitrate consent from the nitrate directive used as a benchmark (EC, 1991)

The highest value recorded was 13.76 mg-N.L⁻¹ and it is the only value over the benchmark of the nitrate directive of 11.3 mg-N.L⁻¹.

LSD table analysis revealed that there were 2 groups of measurements; for both upstream and downstream groundwater samples. In the upstream samples, for the period 30/08/07 to 17/10/07, TON concentrations were significantly lower than for other periods. This period was a period of high PSMD compared to the annual average of 64 mm (August 2007 with PSMD of 91 mm and September, October 2007 with PSMD of 131 mm, Silsoe Met data). This high PSMD would have limited drainage or input or exchange of water from surface to groundwater hence limiting input of nutrients as well. In the downstream samples, the period 06/12/07 to 23/01/08, TON concentrations were significantly higher than for other periods. Rainfall was abundant during that period (over 52 mm.month⁻¹) and PSMD low. Moreover, TON concentrations in soil water sampled at 60 cm under irrigated plots were also presenting a peak at the same period with similar concentrations. Hence, irrigation might explain these high values.

3.3.4.3 TN in groundwater

TN data had to be transformed to ensure residuals normal distribution (Table 9).

Table 9 ANOVA table for log(TN) from both upstream and downstream groundwater sampling (in bold, significant factors, $p < 0.05$)

	<i>Degree of Freedom</i>	<i>log(TN) - F</i>	<i>Log(TN) - p</i>
Intercept	1	88.40	0.00
date(location)	54	3.73	0.00
location	1	40.70	0.00
Error	52		
Total	107		

Downstream samples TN concentrations were significantly greater than upstream TN concentrations; averages for downstream $1.4 \pm 0.8 \text{ mg-N.L}^{-1}$ and $2.8 \pm 2.2 \text{ mg-N.L}^{-1}$ for upstream. Hence, it might mean that the presence of the WaterRenew system at Cranfield site increased significantly TN concentrations in groundwater. And this evolution is in accordance with TON evolution in groundwater.

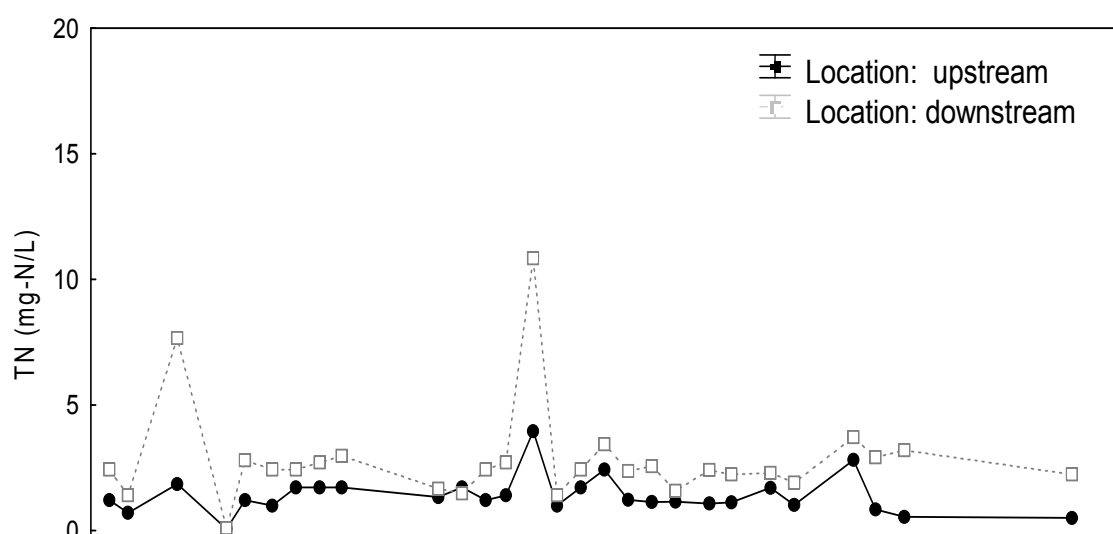


Figure 8 Evolution of TN in upstream and downstream samples from 28/10/06 until 19/05/08. (Vertical bars denote for 0.95 confidence interval.)

There was no date where the average of samples exceeded the 11.3 mg-N.L^{-1} , nitrate directive (DEFRA, 2002) consent used as a benchmark. The fact downstream concentrations were always greater than upstream concentrations could be explained

by the fact the river was also only at 2 m away from the downstream dip wells (Figure 1) and there was no guarantee that there was no exchange between the downstream well groundwater and the river water. The average for TN from soil water sampled at 60 cm under irrigated plots was of $2.5 \pm 2.2 \text{ mg-N.L}^{-1}$, and $2.3 \pm 2.2 \text{ mg-N.L}^{-1}$ for non-irrigated plots. Hence, even under irrigated plots, TN concentrations were lower than downstream TN concentrations. For this reason, the drainage theory with N leaching down to groundwater would be a reasonable explanation. However, it is not possible to reject the theory of river water mixing with downstream water.

3.4 POTASSIUM IN SOIL WATER AND GROUNDWATER

3.4.1 K in soil water

- General descriptive statistics

Table 10 Potassium in soil water, general statistics. (Averaged on soil covers, irrigation and depth), in bold the greater when irrigated and non-irrigated measures are compared.

	<i>Valid N</i>	<i>Mean</i>	<i>Mini- mum</i>	<i>Maxi- mum</i>	<i>Standard Deviation.</i>
Non-irrigated K (mg-K.L⁻¹)	455	12.35	0.00	182.31	22.06
Irrigated K (mg-K.L⁻¹)	682	15.80	0.00	236.95	27.89

The maximum value for K concentration in soil water was greater under irrigated plots with a peak at $236.98 \text{ mg-K.L}^{-1}$ (unplanted plots at 30 cm on the 18/05/08) against $182.31 \text{ mg-K.L}^{-1}$ (eucalyptus, 60 cm on the 17/10/07) for non-irrigated plots (Table 11, Figure 13).

K concentration variability was very high resulting in standard deviations greater than means.

In the effluent, K average concentration was $48.0 \pm 58.9 \text{ mg-K.L}^{-1}$; hence, with averages in soil solution under irrigated plots of $15.80 \pm 27.89 \text{ mg-K.L}^{-1}$, there was a reduction of 70% either by dilution or by soil adsorption. K participates in soil buffer capacity (Rowell, 1994) and in heavy-textured soil like clay, there are very large reserves of exchangeable K that can contribute between 10 to 100 times larger than the amount in the solution. There are 4 categories of exchangeable K in soil, non-exchangeable K⁺, slowly exchangeable K⁺, exchangeable K⁺ and K⁺ in solution. Hence, applied K by irrigation could have entered one of the 3 categories in soil. In Chapter 5, 3.10.1, it was

found that available K concentration in soil increased significantly; hence, this could be explained by this adsorption onto soil matrix.

- **Analysis of variance**

Data had to be transformed to ensure residuals normal distribution.

ANOVA concluded there were significant effects due to all the factors considered, i.e. irrigation, tree presence, depth, date and the interaction of tree and irrigation on K concentrations in soil water (Table 11).

Table 11 ANOVA table for log(K) under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p < 0.05$)

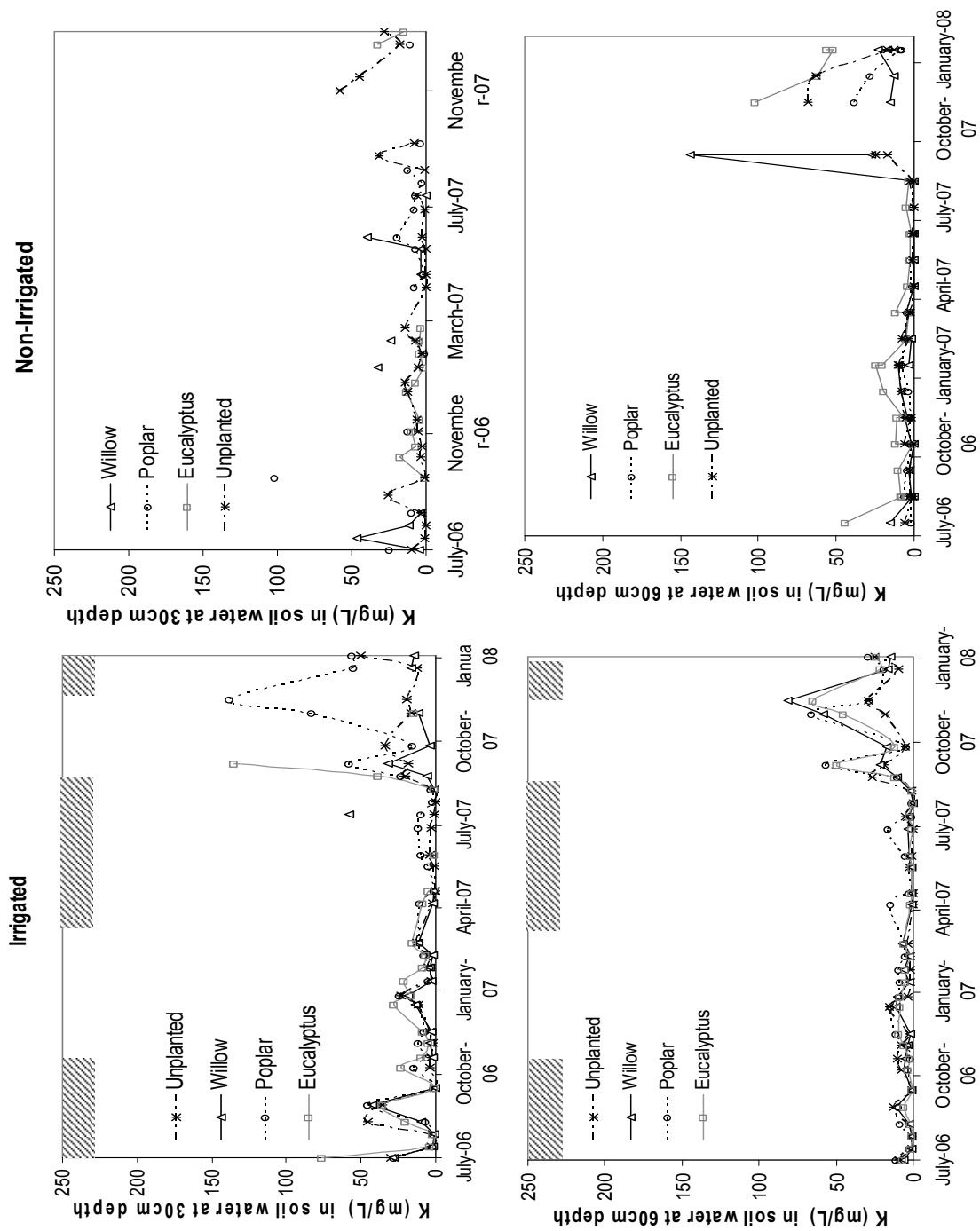
	<i>Degree of Freedom</i>	<i>log(K) - F</i>	<i>log(K) - p</i>
Intercept	1	1861.91	0.00
Cover	3	13.53	0.00
irrigation	1	3.92	0.048
depth(cover*irrigation)	8	7.72	0.00
date(cover*irrigation*depth)	446	3.70	0.00
cover*irrigation	3	2.80	0.04
Error	535		
Total	996		

LSD table analysis revealed irrigation increased significantly K concentration under poplar planted trees and decreased significantly K concentration under eucalyptus.

Then, tree presence increased K concentration for the 3 species but for irrigated plots, significantly only under poplar and eucalyptus and for non-irrigated plots, only under eucalyptus.

Finally, K concentrations at 30 cm were significantly higher than at 60 cm for non-irrigated unplanted plots, willow and poplar and then for irrigated unplanted and eucalyptus (Figure 9).

Figure 9
Evolution of
averaged K
concentration at
30 cm and
60 cm depth,
under
4 covers, U,
W, P, E,
irrigated or
non-
irrigated.
(Dashed
zones
correspond
to period
when
irrigation
was on)



Concentrations were higher under irrigated conditions than non-irrigated ones, however not significantly (Table 12).

Table 12 Potassium in soil water, general statistics. (Averaged on soil covers, irrigation and depth)

<i>depth</i>	<i>30cm</i>	<i>60cm</i>	<i>30cm</i>	<i>60cm</i>
Irrigation	YES	YES	NO	NO
K (mg.L ⁻¹)	8.2	5.1	7.5	5.7
Standard deviation	2.7	1.6	1.6	3.6

In terms of soil and plants buffer capacity, the average concentrations under irrigated plots was 8.2 ± 2.7 mg-K.L⁻¹ at 30 cm and 5.1 ± 1.6 mg-K.L⁻¹ at 60 cm. hence, with an effluent average K concentration of 48.0 ± 58.9 mg-K.L⁻¹, a reduction of 83% at 30 cm and 90% at 60 cm or 38% from 30 cm to 60 cm was observed.

LSD table analysis on K concentration evolution with time, from the 30/08/07, the concentrations in soil solution are higher than in the samples collected before the 30/08/07 for irrigated plots at 30 cm and 60 cm and for non-irrigated plots at 60 cm. For irrigated plots, this sudden increase in K in soil water can be correlated to the fact irrigation rate was doubled from 15 mm.day⁻¹ until 30 mm.day⁻¹ from the 17/08/07 (Figure 9). However, this increase was also measured on non-irrigated plots' samples. This period did not correspond to a period of high rainfall not low PSDM (91 mm in August, 131 mm in September and October). There was no flooding at that period either. Hence, these concentrations are unexpected.

3.4.2 K in groundwater

K data had to be transformed to ensure residuals normal distribution (Table 13).

Table 13 ANOVA table for log(K) from both upstream and downstream sampling (in bold, significant factors, $p < 0.05$)

	<i>Degree of Freedom</i>	<i>log(K) - F</i>	<i>log(K) - p</i>
Intercept	1	1421.02	0.00
date(location)	38	11.47	0.00
location	1	42.28	0.00
Error	39		
Total	78		

Upstream samples K concentrations were significantly lower than downstream K concentrations. And for the period 30/08/07 to the 18/05/08, K concentrations were significantly higher than for other period of measurements. This corresponds to the period when irrigation capacity was doubled and that could explain those high concentrations.

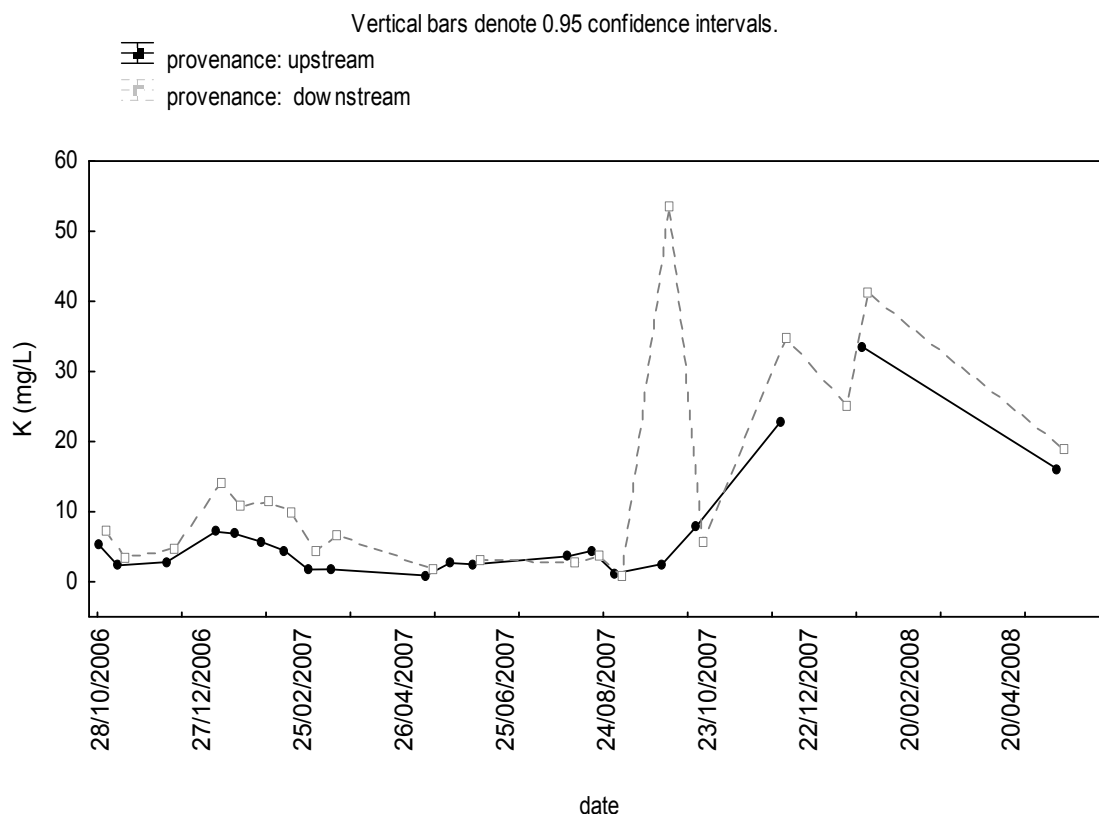


Figure 10 Evolution of K concentrations in groundwater sampled from upstream and downstream the field from 28/10/06 until 18/05/08.

The mean K concentration upstream was of $6.8 \pm 8.3 \text{ mg-K.L}^{-1}$ and $13.2 \pm 14.6 \text{ mg-K.L}^{-1}$ for downstream samples. K was applied by irrigation ($48 \pm 58 \text{ mg-K.L}^{-1}$ in effluent) and soil water K concentration at 60 cm was of $10.8 \pm 14.2 \text{ mg-K.L}^{-1}$ for irrigated plots and of $12.3 \pm 20.6 \text{ mg-K.L}^{-1}$ for non-irrigated plots. Hence, downstream K concentrations could be explained by the presence of the WaterRenew field trial but as for TON, the higher K in downstream samples might be explained by exchange with river water.

3.5 SODIUM IN SOIL WATER AND IN GROUNDWATER

3.5.1 Na in soil water

Na data had to be transformed to ensure residuals normal distribution.

ANOVA revealed that tree presence and irrigation increased significantly Na concentration in soil water ($p < 0.05$ on Table 14).

Table 14 ANOVA table for log(Na) (log as data has been transformed to assure normal distribution of the residuals) in soil water.

	<i>Degree of Freedom</i>	<i>log(Na)</i> <i>- F -</i>	<i>log(Na)</i> <i>- p -</i>
Intercept	1	19544.92	0.00
cover	3	6.20	0.00
irrigation	1	40.27	0.00
depth(tree*irrigation)	8	12.11	0.00
date(tree*irrigation*depth)	429	4.47	0.00
tree*irrigation	3	6.68	0.00
Error	546		
Total	990		

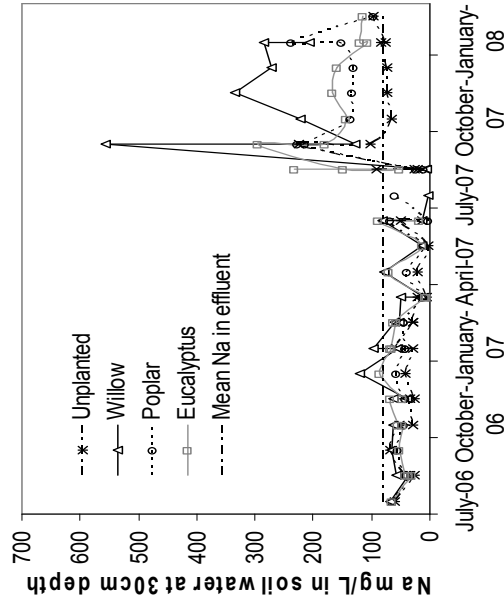
Figure 11 shows the evolution of Na concentrations in soil water at 30 cm and 60 cm depth for all plots from July 2006 until February 2008. The average Na concentration in effluent ($78 \pm 50 \text{ mg-Na.L}^{-1}$) is presented as a dotted line.

Irrigation appeared to have a significant effect on Na concentration in soil water on increasing it at both 30 and 60cm depth. However, irrigation effect became noticeable and after significant from 30/08/07; 2 weeks after the irrigation capacity was doubled up from 15 mm.day^{-1} to 30 mm.day^{-1} .

When looking at unplanted irrigated plots at 30 cm, four zones can be identified:

- July 2006-March 2007 with an average value around 30 mg-Na.L^{-1} ; i.e. half of Na concentration in effluent.
- March 2007-May 2007 with a significant decrease in Na concentration in soil water. The irrigation started on the 20/03/07. The average concentration was around 5 mg-Na.L^{-1} . and remained low until end of August 2007.
- August 2007-September 2007 with a significant increase in Na concentration up to 270 mg-Na.L^{-1} ; 4 times greater than Na in effluent.

Irrigated- Na in wastewater 78 \pm 50mg/L(-.-)



Non-Irrigated

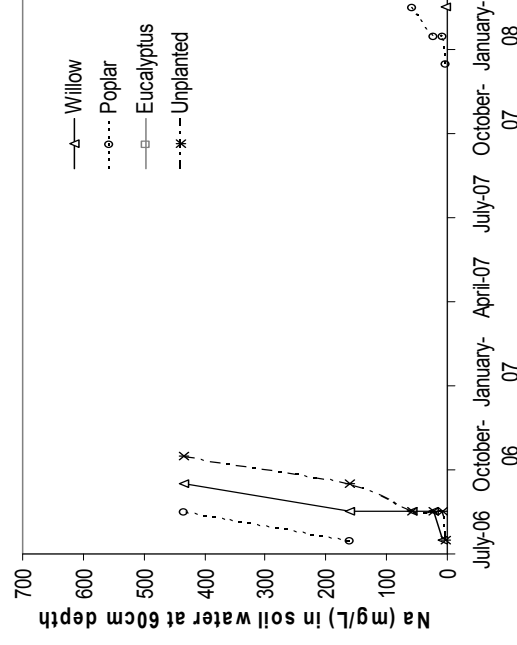
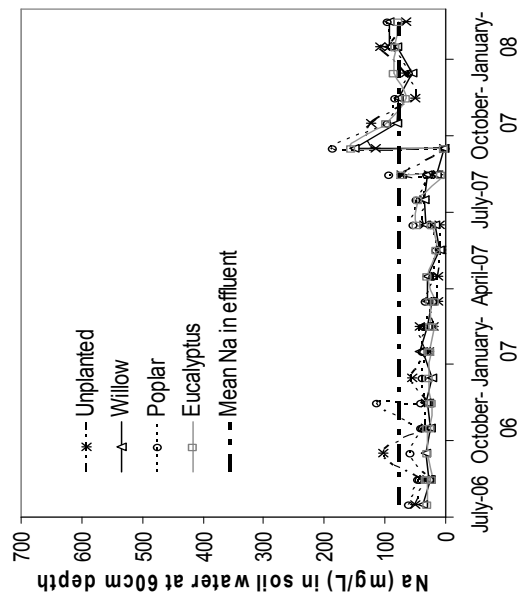
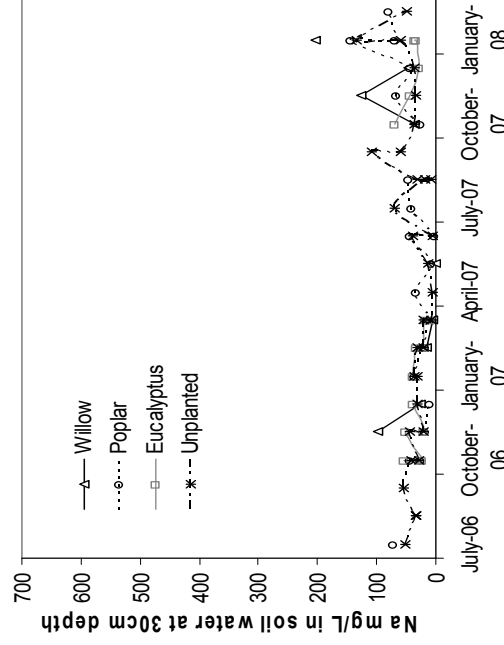


Figure 11
Evolution of Na concentration in soil water at 30 and 60cm depth under irrigated or non-irrigated plots planted with willow, poplar, eucalyptus or unplanted from July 2006 until February 2008 (-.-) mean Na concentration in effluent 78 \pm 50mg-Na/L

- October 2007-Januray 2008 with an average of 70 mg-Na.L⁻¹; i.e. a comparable concentration as in the effluent.

When examining the willow planted irrigated plots at 30 cm, 3 zones can be identified:

- July 2006-March 2007 with an average value around 70 mg-Na.L⁻¹; i.e. comparable to Na concentration in effluent.
- March 2007-May 2007 with a significant decrease in Na concentration in soil water. The average concentration was around 1.4 mg-Na.L⁻¹ and low until end of August 2007.
- August 2007-September 2007 with a significant increase in Na concentration up to 555 mg-Na.L⁻¹; 8 times greater than Na in effluent. Concentrations remained high until the end of the experiment in January 2008 with concentration averaging 250 mg-Na/L; i.e. 4 times greater than the concentration in the effluent.

When looking at poplar planted irrigated plots at 30 cm, 3 zones can be identified:

- July 2006-March 2007 with an average value around 50 mg-Na.L⁻¹; i.e. slightly lower than Na concentration in effluent.
- March 2007-May 2007 with a significant decrease in Na concentration in soil water. The average concentration was around 3 mg-Na.L⁻¹ and remained low until end of August 2007.
- August 2007-January 2008 with a significant increase in Na concentration up to 237 mg-Na.L⁻¹; 3.5 times greater than Na in effluent. Concentrations remained high until the end of the experiment in January 2008 with concentration averaging 170 mg-Na.L⁻¹; i.e. 2.5 time greater than the concentration in the effluent.

When looking at eucalyptus planted irrigated plots at 30cm, 3 zones can be identified:

- July 2006-March 2007 with an average value around 60 mg-Na.L⁻¹; i.e. slightly lower than Na concentration in effluent.
- March 2007-August 2007 with a significant decrease in Na concentration in soil water. The average concentration was around 7 mg-Na/L. and low until end of August 2007.
- August 2007-September 2007 with a significant increase in Na concentration up to 295 mg-Na.L⁻¹; 4.3 times greater than Na in effluent. Concentrations remained high until the end of the experiment in January 2008 with concentration

averaging 250 mg-Na.L⁻¹; i.e. 4 times greater than the concentration in the effluent.

Hence, under all covers, a general trend can be identified; a first stage from July 2006 to March 2007 with Na concentration in soil water comparable to the one in the irrigation effluent. A second stage starts from March until end of August 2007, with a decrease, significant, with on average less than 10% of the concentration of Na in the irrigation effluent. This period corresponds to maximum leaf and stem growth. However, it was also a low soil moisture deficit period, hence with a low irrigation rate. The combination of low Na application and high rain diluted Na in soil water, explains the low values measured. From the 17/08/07, the maximum irrigation capacity doubled from 15 mm.day⁻¹ to 30 mm.day⁻¹. It was followed by a drier period and water demand was still high with trees in leaf and development. Hence, the peak observed under all covers on the 13/09/07 can be partly explained by the replacement of soil water solution with effluent. Before that, Na applied was probably exchanged with other cation in soil matrix and therefore adsorbed and not in solution anymore (Jalali et al., 2008). However, the Na concentrations observed were especially high (ranging from 3.5 times to 8 times higher than concentration in effluent) on that date but remained very high until the end of the experiment in January 2008 for planted plots. Therefore, Na has to come from another source than the actual applied effluent, in other words, the concentration observed can not only be effluent Na not exchanged anymore on the soil CEC. Na applied previously must have precipitated or being adsorbed and is released subsequent to soil structural loss (Jalali et al., 2008).

For unplanted plots, soil water Na concentrations were comparable to Na concentration in effluent.

However, a great proportion of Na applied was not fixed by soil as over 1.4 ton-Na.ha⁻¹ was applied in average (Chapter 5, 3.3) but soil Na extracted in ammonia nitrate only increased by 59 mg-Na.kg⁻¹ of soil which correspond to an increase of 432 kg.ha⁻¹ for soil from 0-60 cm depth. Drained volumes were not determined, hence the amount of Na leached by drainage is not known (will be calculated in Chapter7) but almost a tonne of Na is missing per hectare in soil at the end of the experiment compared to the amount applied.

Jalali (Jalali et al., 2008) described a release of Na when soil were irrigated with wastewater and subsequently irrigated with water of a greater quality. Therefore, Na concentration in effluent was observed (Figure 12). There was no quality improvement

but the effluent was more saline with time with a high variability and the possibility to have very high concentrations (cf. Figure 12, slope of the linear regression is positive $0.1537 > 0$, and the high value of 200 mg-L^{-1} in May 2007). Therefore, the higher Na concentrations in soil water from September 2007 must result from first the fact that no Na from effluent is exchanged on the CEC of soil matrix, and second, some Na starts to leach from the saturated CEC.

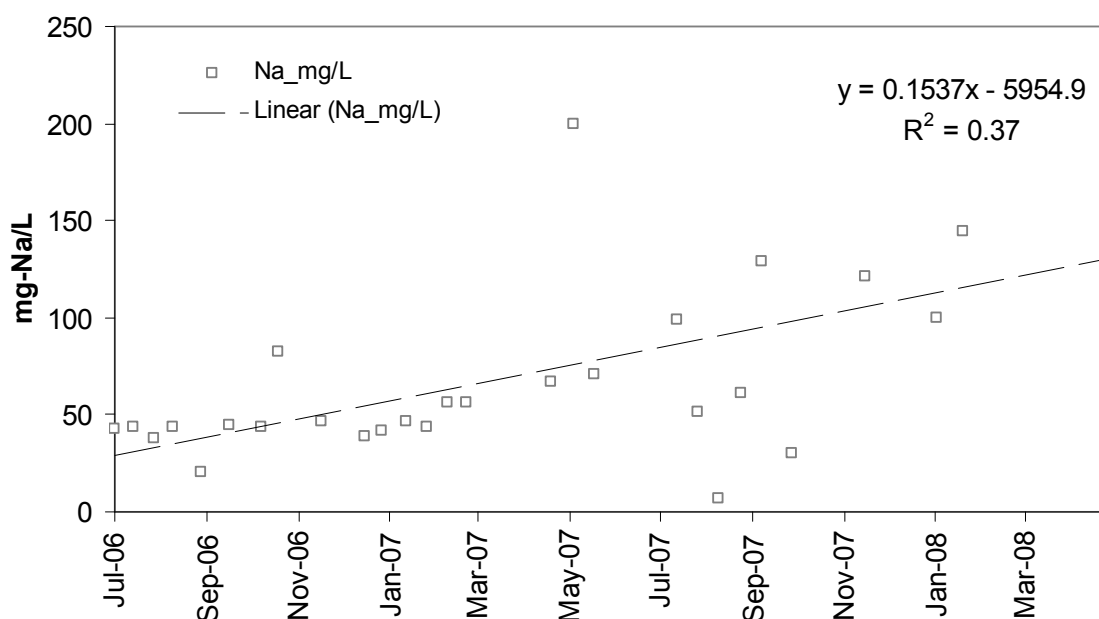


Figure 12 Evolution of Na concentration in effluent used for irrigation from July 2006 to May 2008 on samples collected fortnightly.

3.5.2 Na in groundwater

Na data had to be transformed to ensure residuals normal distribution (Table 15).

Table 15 ANOVA table for $\log(\text{Na})$ from both upstream and downstream sampling (in bold, significant factors, $p < 0.05$)

	<i>Degree of Freedom</i>	<i>log(K) - F</i>	<i>log(K) - p</i>
Intercept	1	7523.52	0.00
date(location)	42	6.79	0.00
location	1	64.37	0.00
Error	44		
Total	87		

Upstream samples Na concentrations were significantly higher than downstream Na concentrations. Hence, either the presence of the WaterRenew system and adsorption

of Na through the soil matrix under the WaterRenew system or dilution of downstream groundwater with river water might have contributed to lower Na concentration between upstream and downstream samples. Compared to effluent concentration ($69.7 \pm 47.3 \text{ mg-Na.L}^{-1}$) upstream average concentration was of $66.5 \pm 45.0 \text{ mg-Na.L}^{-1}$ and downstream average concentration was of $40.9 \pm 35.6 \text{ mg-Na.L}^{-1}$. Hence, downstream concentrations were 59 % of effluent concentrations and irrigation of the plots did not affect downstream groundwater concentrations.

The pattern between the upstream concentrations and downstream concentrations were similar.

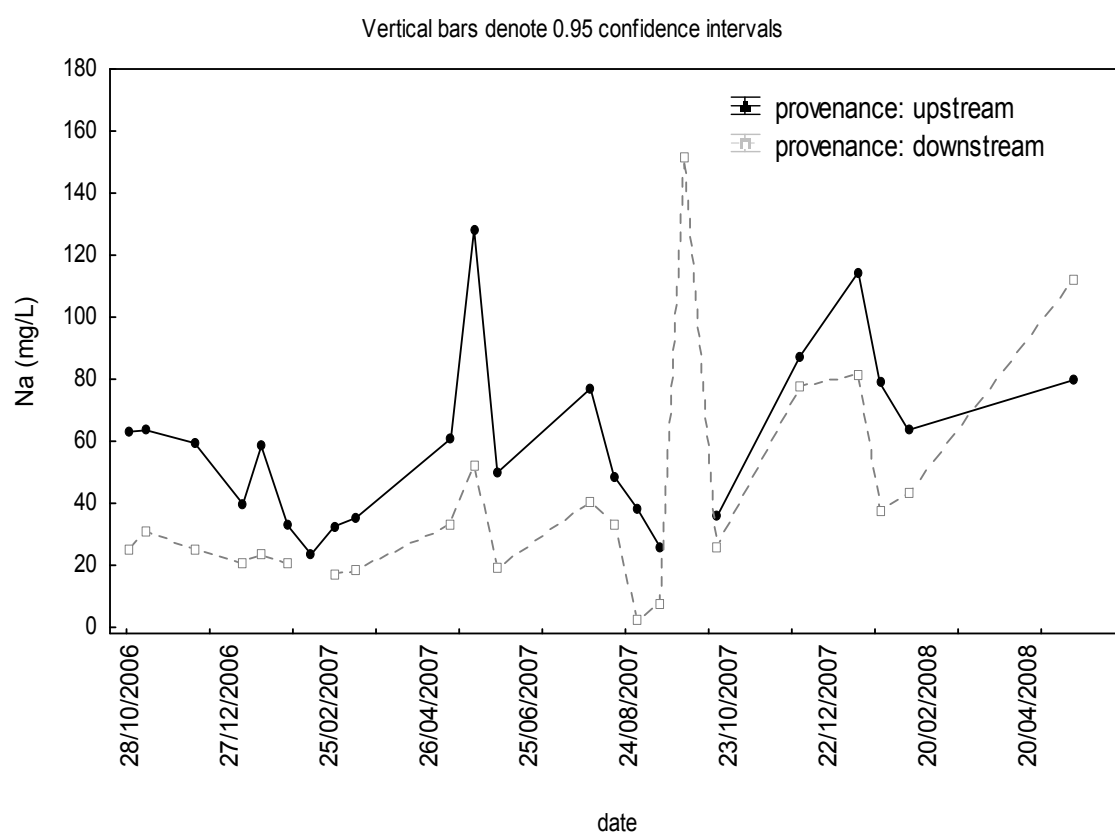


Figure 13 Evolution of Na concentration in groundwater from the 28/10/06 until 18/05/08.

3.6 PH AND EC IN SOIL WATER AND GROUNDWATER

3.6.1 pH and EC in soil water

When the amount sampled was less than 5 mL, samples were diluted with distilled water but on diluted samples, neither pH nor EC were measured. Moreover, as soil solution was sampled on applying -60 kPa depression to soil water suction cup

samples for 24 hour, and the measurements conducted then, pH and EC are probably not representative of real pH and EC of soil solution. For this reason, the following analyses are indicative.

For pH, even after log transformation, residuals couldn't be normalised, hence, ANOVA was not possible.

Means plots (with 0.95 confidence interval) (Figure 14) were homogenised with irrigation; the variability is not significant for irrigated plots but for non-irrigated plots, unplanted plots soil solution was significantly more alkaline than under willow and poplar. Effluent pH was measuring 7.2 ± 0.5 , hence slightly alkaline. However, from Figure 14, irrigated plots pH were not significantly different from non-irrigated plots ones; willow and poplar presence tend to lower pH but not eucalyptus. This might be due to the fact that willow and poplar lose their leaves during autumn, providing organic matter (acidic, (Rowell, 1994)) but eucalyptus trees do not. Under all plots, soil water pH was higher than in soil (average $\text{pH}_{\text{soil}} = 7.6$).

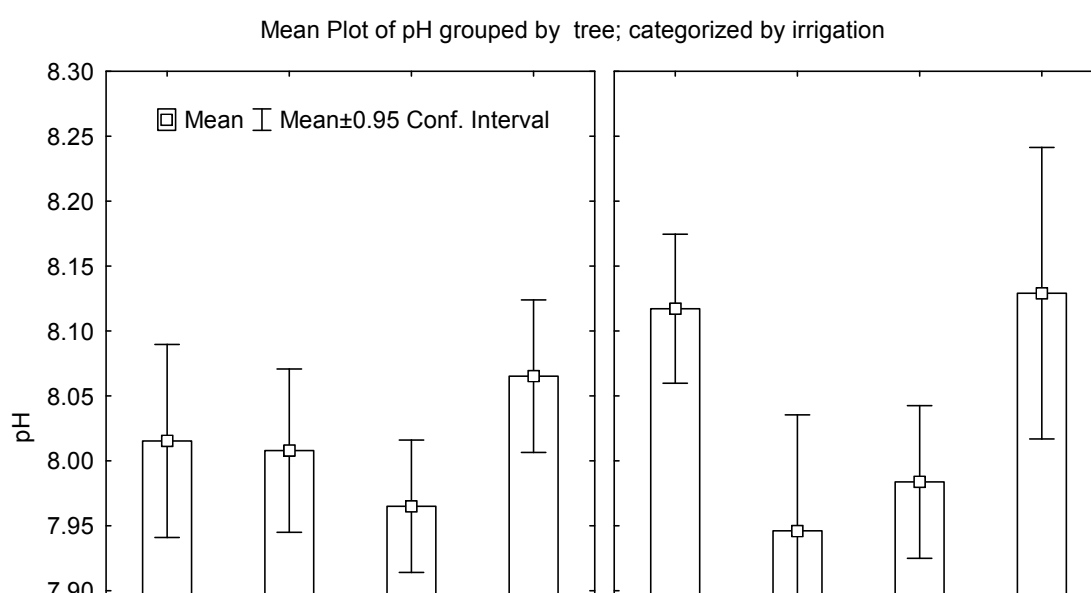


Figure 14 Mean of pH with 0.95 confidence interval averaged by cover, and if plot is irrigated and non-irrigated.

For EC:

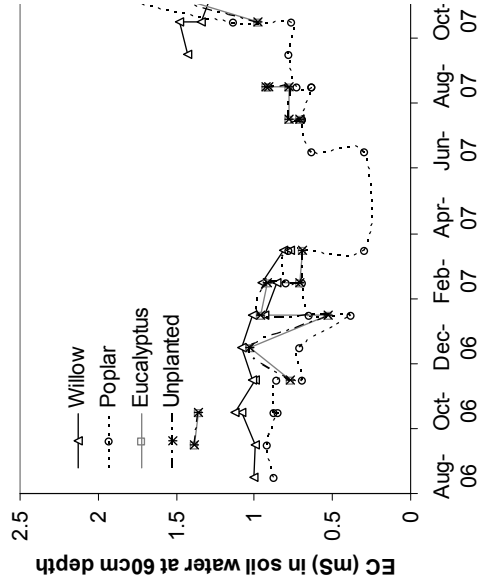
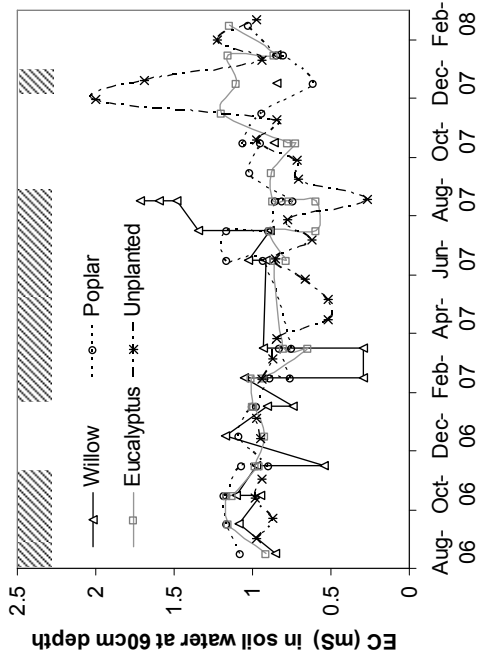
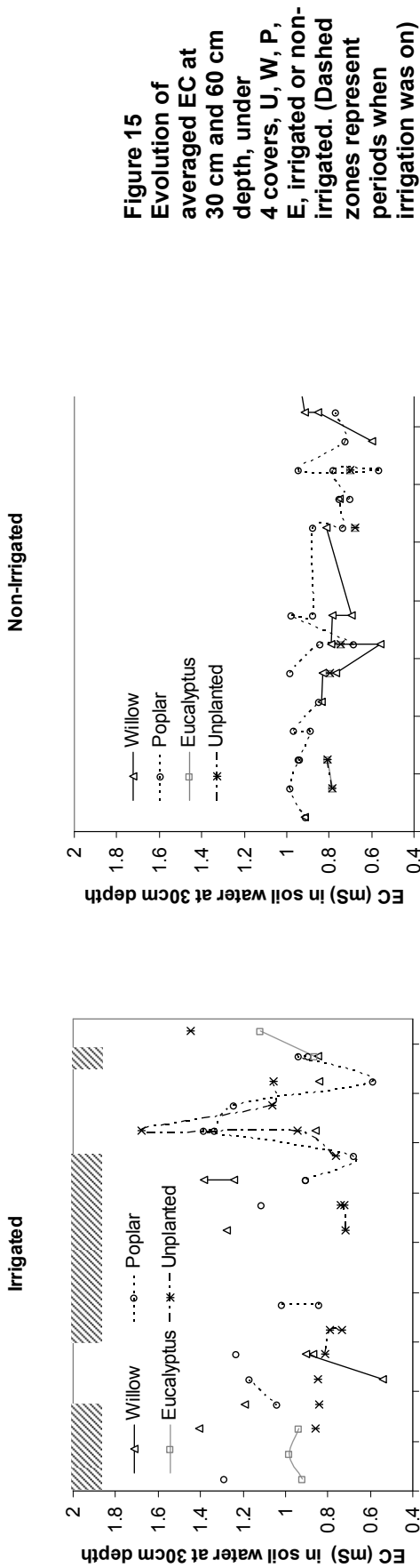
Data had to be transformed to ensure residuals normal distribution.

ANOVA concluded there were significant effects of all the factors considered, i.e. irrigation, tree presence, depth, date and the interaction of tree and irrigation on EC in soil water (Table 16).

Table 16 ANOVA table for log(EC) under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p < 0.05$)

	<i>Degree of Freedom</i>	<i>log(EC) - F</i>	<i>log(EC) - p</i>
Intercept	1	67.75	0.00
tree	3	11.83	0.00
irrigation	1	15.18	0.00
depth(tree*irrigation)	8	6.60	0.00
date(tree*irrigation*depth)	227	1.62	0.00
tree*irrigation	3	2.74	0.04
Error	224		
Total	466		

EC evolution during the period of monitoring (Figure 15) does not have a particular trend. Irrigated plots EC at 30 cm appeared to be greater than under non-irrigated conditions; however, the scarcity of measurement points makes judgement difficult.



3.6.2 pH and EC in soil water

For ANOVA relevance, residuals need to follow a normal distribution (McBean and Rovers, 1998) (details in Chapter 3, 4, 4.1.2). This was the case for pH data.

Table 17 ANOVA table for pH from both upstream and downstream sampling (in bold, significant factors, $p < 0.05$)

	<i>Degree of Freedom</i>	<i>pH - F</i>	<i>pH - p</i>
Intercept	1	63353.47	0.00
date(location)	40	2.32	0.00
location	1	32.88	0.00
Error	42		
Total	83		

Upstream samples were statistically significantly different from downstream samples pH, however, in terms of pH they were only slightly more acidic pH than downstream samples ($\text{pH} = 7.5 \pm 0.3$ against $\text{pH} = 7.9 \pm 0.3$).

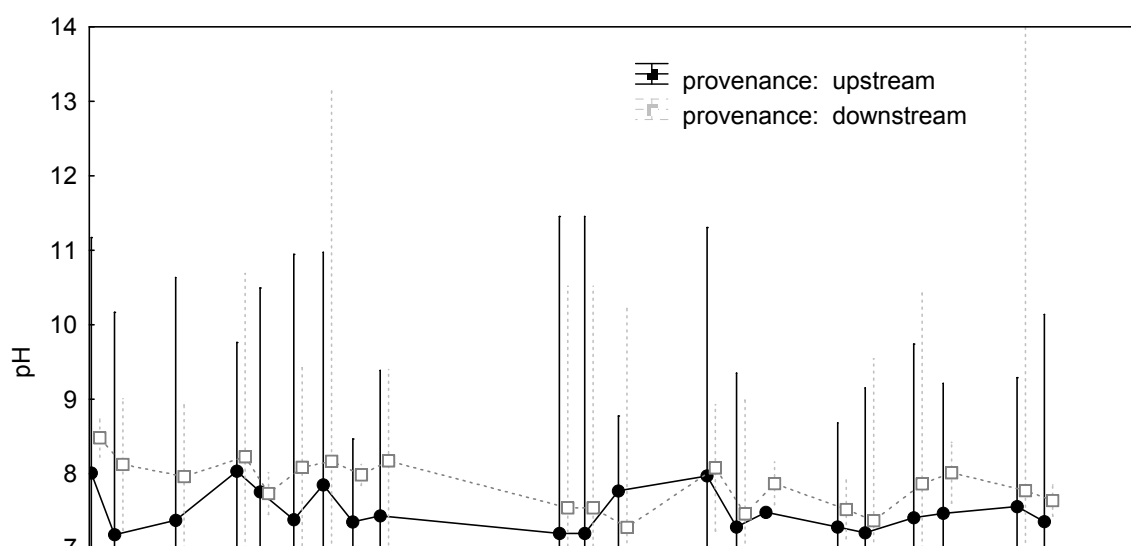


Figure 16 Evolution of pH from upstream and downstream samples from 28/10/06 until 11/02/08.

4. CONCLUSION

When considering the previous results; i.e. concentrations of N,P, K and Na in soil water and groundwater, the implementation of a WaterRenew system on a chalky clayey soil in Cranfield, Bedfordshire, UK, was successful. In effect, for N and P, one of the major concerns and risks for this kind of technology (Scott et al., 2000) is a lack of significant effect of irrigation with secondary treated effluent on SRC even on a chalky clayey soil on which vertical treatment is not recommended (Tyrrel and Leeds-Harrison, 2005).

The specific objectives of this soil water and groundwater analysis were to:

- **Objective 1:** identify and quantify significant changes in soil water and groundwater chemistry as a result of effluent tertiary treatment, i.e. N and P removal, and effectiveness.

One of the major environmental risks of a WaterRenew system is the potential pollution of groundwater by non-adequately treated effluent or inadequate N and P removal. Soil water quality at the bottom of the system fixed at 60 cm depth and comparison of groundwater quality upstream and downstream the field are good indicators of the effectiveness of the system in terms of nutrient removal. According to the chemical analysis results for soil water and groundwater, the implementation of a WaterRenew system in Cranfield University sewage treatment work did not have an adverse effect with no negative impact on soil water and groundwater compartments. In other words, secondary treated effluent polishing was successful on this site and nutrients, N and P, removal efficient.

- For the N story, soil water N was not affected by irrigation; in particular, N concentration in soil water was not increased by irrigation. TN concentrations in soil water were significantly lower than in the effluent: $TN_{30cm} = 3.5 \text{ mg-N.L}^{-1}$ and $TN_{60cm} = 2.5 \text{ mg-N.L}^{-1} < TN_{effluent} = 30.0 \text{ mg-N.L}^{-1}$. Therefore, the efficiency of the system to remove TN from effluent was over 88 % at 30 cm and over 92 % at 60 cm.
- For the P story, it is assumed that soil adsorbed the majority of P applied by irrigation, and some P was also uptaken by trees so that P concentration in soil water was lower than the limit of detection. Therefore, from a soil water point of view, the effectiveness of P removal is 100 % for the WaterRenew system.

However, the story was different for K and Na evolution in soil water and groundwater:

- Irrigation had a significant effect on increasing K concentrations in soil water (averaged concentrations: $K_{\text{irrigated}}=14.7 \text{ mg-K.L}^{-1} > K_{\text{non-irrigated}}=12.7 \text{ mg-K.L}^{-1}$). Moreover; downstream groundwater samples presented significantly higher K concentrations than in upstream groundwater samples ($K_{\text{upstream}}=6.8 \text{ mg-K.L}^{-1} < K_{\text{downstream}}=13.2 \text{ mg-K.L}^{-1}$) which could be explained by drainage leaching K from soil water into groundwater.
 - Irrigation had a significant effect on increasing Na concentrations in soil water (averaged concentrations: $\text{Na}_{\text{non-irrigated}}=63.04 \text{ mg-Na.L}^{-1} < \text{Na}_{\text{irrigated}}=77.23 \text{ mg-Na.L}^{-1}$). However; downstream groundwater samples presented significantly lower Na concentrations than in upstream groundwater samples ($\text{Na}_{\text{upstream}}=66.5 \text{ mg-Na.L}^{-1} > \text{Na}_{\text{downstream}}=40.9 \text{ mg-Na.L}^{-1}$). The effluent Na concentration was of $69.7 \text{ mg-Na.L}^{-1}$, hence all the concentrations measured were in the same range. Na in the irrigation water did concentrate in soil water but not enough to increase the concentration in groundwater.
- **Objective 2:** assess the relative importance of soil and trees on soil water chemistry changes, i.e. their relative importance in the effectiveness of a WaterRenew system as a wastewater tertiary treatment.

The system is proven efficient on removing N and P from secondary treated effluent. Soil water samples were taken under all plots, in particular planted and unplanted, and at two depths, 30 cm, in the maximum root density zone, and 60 cm, considered as the bottom of the system in Cranfield. Hence, it was possible to compare tree presence effect on both N and P removal efficiencies.

- For the N story, tree uptake, tree presence and subsequent organic matter development by root growth and activity had a significant effect on decreasing soil water N concentrations. There was a species effect for 30 cm, where maximum root densities are located in this zone for poplar, willow and eucalyptus (Crow and Houston, 2004). For the irrigated plots with poplar and willow soil water N concentrations decreased significantly compared to eucalyptus trees at 30 cm. However, there was no tree effect at 60 cm.
- For the P story, a soil buffer capacity was shown as there was no P detectable in the soil water sampled under irrigated unplanted plots. As in soil, P

removal from solution is occurring through adsorption processes and the soil adsorption capacity is finite, this WaterRenew system will not be able to remove P indefinitely. As this experiment was conducted for a short time period, the long term perspective can not be forecasted. Therefore, an independent column experiment was set up to try to assess the sustainability of P removal by Cranfield soil (Chapter 8).

- For the K story, tree presence had an effect contrary to that which was expected. There was a significant concentration of K in soil water from planted plots ($K_{\text{unplanted},60\text{cm}}=8.75 \text{ mg-K.L}^{-1} < K_{\text{planted},60\text{cm}}=12.47 \text{ mg-K.L}^{-1}$) and lower concentration at 60 cm. Therefore, K removal capacity lies in soil mainly.
- For the Na story, tree presence also significantly increased Na concentration ($\text{Na}_{\text{unplanted},30\text{cm}}=51.53 \text{ mg-Na.L}^{-1} < \text{Na}_{\text{planted},30\text{cm}}=88.20 \text{ mg-Na.L}^{-1}$). This is probably because trees absorbed water from the effluent but did not uptake Na, hence Na became more concentrated. Moreover, there were higher concentrations measured at 60 cm ($\text{Na}_{30\text{cm}}=59.44 \text{ mg-Na.L}^{-1} > \text{Na}_{60\text{cm}}=80.82 \text{ mg-Na.L}^{-1}$).

In terms of overall tree species “performance” comparison, when considering only the soil water chemistry, poplar performed the best as soil water under poplar planted plots presented the lowest concentrations for K and Na and second low for TN (lowest being willow). The major part for nutrient removal in the WaterRenew system is soil, as although tree effect could be significant, it was not as important as the functions of the soil.

5. REFERENCES

- Aronsson, P. and Perttu, K. (2001), "Willow vegetation filters for wastewater treatment and soil remediation combined with biomass production.", *Forestry Chronicle*, vol. 77, no. 2, pp. 293-299.
- Aronsson, P. G. and Bergstrom, L. F. (2001), "Nitrate leaching from lysimeter-grown short-rotation willow coppice in relation to N-application, irrigation and soil type", *Biomass and Bioenergy*, vol. 21, no. 3, pp. 155-164.
- Aronsson, P. G., Bergstrom, L. F. and Elowson, S. N. E. (2000), "Long-term influence of intensively cultured short-rotation Willow Coppice on nitrogen concentrations in groundwater", *Journal of Environmental Management*, vol. 58, no. 2, pp. 135-145.
- Baert, R., Loontjens, R. and Devos, M. (April 22-26, 1996), "Potassium and Nitrate pollution of surface water in the catchment area of the "Blankaert" water production centre in Flanders (Belgium)", *Proceedings Fourth International Conference on Environmental Compliance and Enforcement*, .

- Brady, N. C. and Weil, R. R. (eds.) (2001), *The Nature and Properties of Soils*. Prentice Hall, New York.
- Braskerud, B. C. (2002), "Factors affecting phosphorus retention in small constructed wetlands treating agricultural non-point source pollution", *Ecological Engineering*, vol. 19, no. 1, pp. 41-61.
- Cortina, J., Romanyà, J. and Vallejo, V. R. (1995), "Nitrogen and phosphorus leaching from the forest floor of a mature *Pinus radiata* stand", *Geoderma*, vol. 66, no. 3-4, pp. 321-330.
- Crow, P. and Houston, T. J. (2004), "The influence of soil and coppice cycle on the rooting habit of short rotation poplar and willow coppice", *Biomass and Bioenergy*, vol. 26, no. 6, pp. 497-505.
- DEFRA (2002.a), *Growing short rotation coppice : best practice guidelines for applicants to DEFRA's energy crops scheme*. DEFRA, London.
- DEFRA (2002.b), *Sewage treatment in the UK : UK implementation of the EC Urban Waste Water Treatment Directive : sensitive areas : September 2002*, Department for Environment, Food & Rural Affairs, London.
- DEFRA (2002), *Implementation of the Nitrates Directive (91/676/EEC), Description of the methodology applied by the Secretary of State in identifying additional Nitrate Vulnerable Zones in England*. Water Quality Division, 1.
- Dimitriou, I. and Aronsson, P. (2004), "Nitrogen leaching from short-rotation willow coppice after intensive irrigation with wastewater", *Biomass and Bioenergy*, vol. 26, no. 5, pp. 433-441.
- Djodjic, F., Borling, K. and Bergstrom, L. (2004), "Phosphorus Leaching in Relation to Soil Type and Soil Phosphorus Content", *Journal of Environmental Quality*, vol. 33, no. 2, pp. 678-684.
- EC (2000.), *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy*. Office for Official Publications of the European Communities, Luxembourg.
- EC (1991), *Council Directive 1991/676/EEC of the Council of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources*. Office for Official Publications of the European Communities, Luxembourg.
- EUREAU (1993), "Updated comments on the Revision of the Drinking Water Quality Directive 80/778", .
- Harris, W. G., Rhue, R. D., Kidder, G., Brown, R. B. and Littell, R. (1996), "Phosphorus Retention as Related to Morphology of Sandy Coastal Plain Soil Materials", *Soil Sci Soc Am J*, vol. 60, no. 5, pp. 1513-1521.
- Insam, H. and Palojarvi, A. (1995), "Effects of forest fertilization on nitrogen leaching and soil microbial properties in the Northern Calcareous Alps of Austria", *Plant and Soil*, vol. 168-169, no. 1, pp. 75-81.
- Isermann, K. (1994), "Present situation and demands to sustainability in agriculture, human nutrition and waste (water) management of the developed countries in the

- background of their nutrient balances (Summary).", *-Workshop on: Materials Management for Regional Sustainability (MM-ARS), TU Wien/ETH Zürich - Wien, 24.-28. April 1994.*, .
- Jalali, M., Merikhpour, H., Kaledhonkar, M. J. and Van Der Zee, S. E. A. T. M. (2008), "Effects of wastewater irrigation on soil sodicity and nutrient leaching in calcareous soils", *Agricultural Water Management*, vol. 95, no. 2, pp. 143-153.
- McBean, E. A. and Rovers, F. A. (1998), *Statistical procedures for analysis of environmental monitoring data and risk assessment*, Prentice Hall PTR, Upper Saddle River, N.J.
- Mengel, K. (1985), "Dynamics and Availability of Major Nutrients in Soils", in Stewart, B. A. (ed.) *Advances in Soil Science*, Springer-Verlag, NY, Berlin, Heidelberg, Tokyo, pp. 65-131.
- Nahm, K. H. (2005), "Factors influencing nitrogen mineralization during poultry litter composting and calculations for available nitrogen.", *World's Poultry Science Journal*, vol. 61, pp. 238-255.
- Official Journal (OL L 135, 30.05.1991, p.40), (1991), *Urban Waste Water Directive, 91/271/EEC, Directive as amended by the Commission Directive 98/15/EC (OJ, L 67, 07.03.1998, p.29)* ., European Directive ed.
- Rowell, D. L. (1994), *Soil science : methods and applications*, Longman Scientific & Technical, Harlow.
- Scott, C. A., Zarazúa, A. J. and Levine, G. (2000), "Urban-Wastewater Reuse for Crop Production in the Water-Short Guanajuato River Basin, Mexico.", *IIMI Research Report*, vol. 41.
- Smith, C. J., Snow, V. O., Polglase, P. J. and Probert, M. E. (1999), "Nitrogen dynamics in a eucalypt plantation irrigated with sewage effluent or bore water", *Australian Journal of Soil Research*, vol. 37, no. 3, pp. 527-544.
- Tyrrel, S. F. and Leeds-Harrison, P. B. (2005), "Treatment of dirty water from dairy farms using a soil-based batch recirculation system.", *Water Science And Technology*, vol. 51, pp. 73-79.

Figure 1 Cranfield site field trial map, localisation of 24 randomly distributed plots, 3 replicates of 4 covers, unplanted, eucalyptus, willow and poplar, irrigated or not.	4
Figure 2 Evolution of TP concentrations on from upstream and downstream samples collected fortnightly from 28/10/06 until the 18/05/08. (vertical bars denote 0.95 confidence interval).....	10
Figure 3 Evolution of averaged ammonia concentration in soil water at 30 cm and 60 cm depth, under 4 covers, U, W, P, E, irrigated or non-irrigated. (-.-) represents the 1.5 mg-N.L ⁻¹ Ammonia consent from UWWD (2003)- (Dashed Zones represent when irrigation was on.	12
Figure 4 Evolution of averaged TON concentration at 30 cm and 60 cm depth, under 4 covers, U,W, P, E, irrigated or non-irrigated. (-.-) represents the 11.3 mg-N.L ⁻¹ Nitrate standard from Drinking Water Directive (2003) (Dashed area for when irrigation was on).....	15
Figure 5 Evolution of averaged TN concentration in soil water at 30 cm and 60 cm depth, under 4 covers, U, W, P, E, irrigated or non-irrigated (Dashed zone represent when irrigation was on).....	18
Figure 6 Evolution of ammonia in upstream and downstream groundwater samples from 28/10/06 until 19/05/08. (vertical bars denote 0.95 confidence interval)	20
Figure 7 Evolution of TON in upstream and downstream samples from 28/10/06 until 19/05/08. (- -) 11.3 mg-N.L ⁻¹ nitrate consent from the nitrate directive used as a benchmark (EC, 1991).....	22
Figure 8 Evolution of TN in upstream and downstream samples from 28/10/06 until 19/05/08. (Vertical bars denote for 0.95 confidence interval.)	23
Figure 9 Evolution of averaged K concentration at 30 cm and 60 cm depth, under 4 covers, U, W, P, E, irrigated or non-irrigated. (Dashed zones correspond to period when irrigation was on).....	26
Figure 10 Evolution of K concentrations in groundwater sampled from upstream and downstream the field from 28/10/06 until 18/05/08.	28
Figure 11 Evolution of Na concentration in soil water at 30 and 60cm depth under irrigated or non-irrigated plots planted with willow, poplar, eucalyptus or unplanted from July 2006 until February 2008 (-.-) mean Na concentration in effluent 78±50mg-Na/L	30
Figure 12 Evolution of Na concentration in effluent used for irrigation from July 2006 to May 2008 on samples collected fortnightly.	33
Figure 13 Evolution of Na concentration in groundwater from the 28/10/06 until 18/05/08.	34
Figure 14 Mean of pH with 0.95 confidence interval averaged by cover, and if plot Is irrigated and non-irrigated.....	35
Figure 15 Evolution of averaged EC at 30 cm and 60 cm depth, under 4 covers, U, W, P, E, irrigated or non-irrigated. (Dashed zones represent periods when irrigation was on).....	37
Figure 16 Evolution of pH from upstream and downstream samples from 28/10/06 until 11/02/08.	38

Table 1 Average composition of effluent used for irrigation. (Relative concentration in relation with N as TN=100, n/a; non applicable)	6
Table 2 Comparison of the relative concentrations of N, P, K in the different municipal wastes, optimum composition for SRWC, Eucalyptus and Poplar nutrients uptake in relation to N=100, adapted from Aronsson and Perttu 2001.....	7
Table 3 Descriptive statistics on phosphate and TP data from irrigated and non-irrigated plots, at 2 depths (30 cm and 60 cm) and under all covers (unplanted, willow, poplar, eucalyptus).....	8
Table 4 ANOVA table for log(TP) from both upstream and downstream sampling (in bold, significant factors, $p<0.05$)	9
Table 5 ANOVA table for log(NH ₄) in soil water under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p<0.05$)	11
Table 6 ANOVA table for log(TON) under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p<0.05$)	14
Table 7 ANOVA table for log(TN) under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p<0.05$)	17
Table 8 ANOVA table for log(TON) from both upstream and downstream groundwater samples (in bold, significant factors, $p<0.05$).....	21
Table 9 ANOVA table for log(TN) from both upstream and downstream groundwater sampling (in bold, significant factors, $p<0.05$).....	23
Table 10 Potassium in soil water, general statistics. (Averaged on soil covers, irrigation and depth), in bold the greater when irrigated and non-irrigated measures are compared.	24
Table 11 ANOVA table for log(K) under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p<0.05$)	25
Table 12 Potassium in soil water, general statistics. (Averaged on soil covers, irrigation and depth).....	27
Table 13 ANOVA table for log(K) from both upstream and downstream sampling (in bold, significant factors, $p<0.05$)	27
Table 14 ANOVA table for log(Na) (log as data has been transformed to assure normal distribution of the residuals) in soil water.	29
Table 15 ANOVA table for log(Na) from both upstream and downstream sampling (in bold, significant factors, $p<0.05$)	33
Table 16 ANOVA table for log(EC) under 4 covers (W,P,E,U), irrigated or not, and at 2 depths (30 cm and 60 cm) (in bold, significant factors, $p<0.05$)	36
Table 17 ANOVA table for pH from both upstream and downstream sampling (in bold, significant factors, $p<0.05$).....	38

CHAPTER 7 : NUTRIENT BALANCES IN A WATERRENEW SYSTEM

1. INTRODUCTION

A WaterRenew system is a system where wastewater polishing is coupled with fast growing woody crops production. Fates of nitrogen (N) applied to similar systems were studied for clay and sand with willow grown in lysimeters with different treatments in even extreme conditions in Sweden (Aronsson and Bergstrom, 2001; Dimitriou and Aronsson, 2004). It was found that if irrigation was not conducted during the year of establishment, N leaching was very low and thus a willow vegetation filter could be considered seriously as a nutrient treatment in wastewater.

Similar findings were noted for eucalyptus: (*E.grandis*) studies were conducted to understand and quantify nutrients fate of N in plantations irrigated with wastewater in Australia (Smith et al., 1999). They concluded that N leaching happens (53 % of the total N applied) and it takes place mainly during the first year (75%).

However, responses of a SRC to irrigation with wastewater under UK specific edapho-climatic conditions had not been studied yet. Therefore, a small scale (12.25 m²), short rotation coppice (SRC¹) was irrigated secondary treated effluent at the Cranfield University (Bedfordshire, UK) sewage treatment work, on a chalky clayey soil. The manner in which the nutrients applied by irrigation travelled within the different compartments (plant, soil matrix and soil water) constituting the WaterRenew system was monitored and has been discussed in previous chapters (cf. summary Figure1).

Firstly, performances of 3 SRC species, *E. gunnii*, *S. viminalis* and *P. trichocarpa* in terms of water uptake, nutrient uptake and yield production were measured and described (Chapter 4). It concluded that irrigation had a significant positive effect on all the trees' growth and yield, as on N and P concentrations. Eucalyptus trees performed best with the greatest yields, the greatest nutrient uptake and the second greatest water use.

Then, soil samples were collected at 10 cm, 30 cm and 50 cm in February 2006, 2007 and 2008 and were analysed for nutrients content and evolution (Chapter 5). Although

¹ SRC: "coppice densely planted, high-yielding varieties of either willow or poplar, harvested on a 2 –5 year cycle, although commonly every 3years" (DEFRA, 2002.).

the WaterRenew system did not change significantly N, P and K soil pool, there was a slight but significant acidification and salinisation because of irrigation. The presence of tree had had a small impact on soil chemistry.

Finally, soil water quality at 30 cm and 60 cm depth were monitored fortnightly and no significant effect of irrigation was observed on N or P content. However, it was noted that upstream groundwater N concentrations were significantly lower than downstream N concentrations and significantly greater upstream than downstream for groundwater P concentrations (Chapter 6).

Therefore, in order to assess the efficiency or performance of a WaterRenew system, nutrient balances needed to be calculated as an estimation of nutrients fate. This process will thus be the focus of this chapter (Chapter 7, cf. Figure 1).

Thesis outline: nutrients fate and compartments of a WaterRenew system

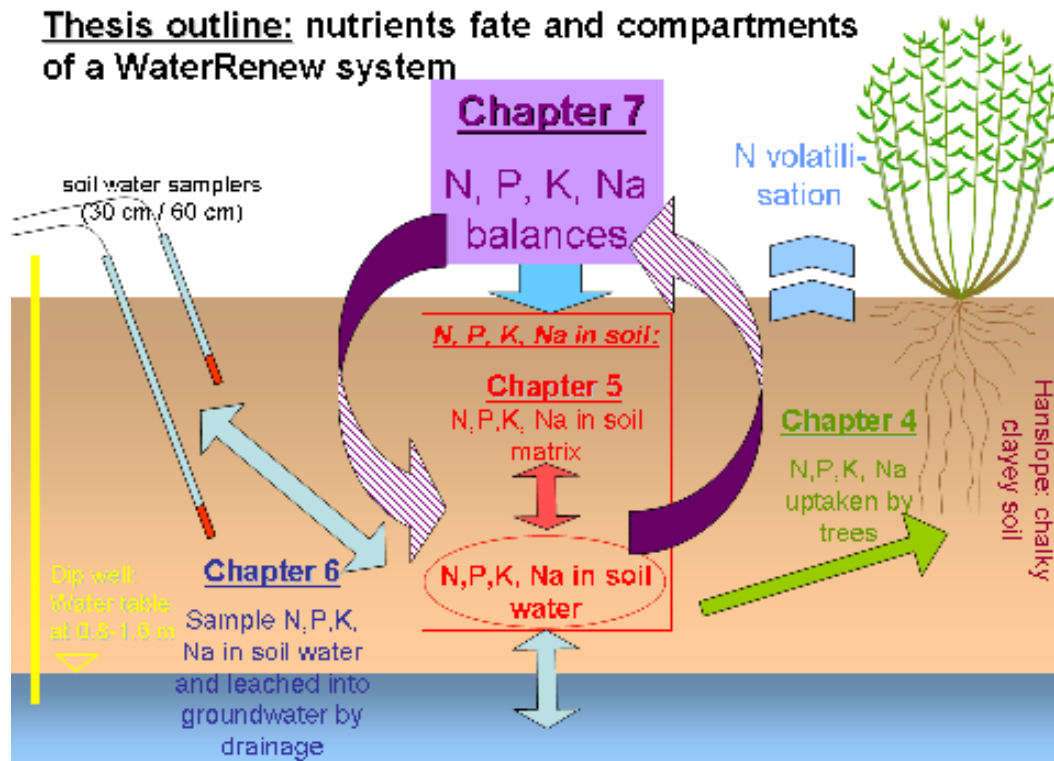


Figure 1 Thesis outline with nutrients (N, P, K, and Na) fate and interactions between the different compartments of a WaterRenew system (soil, soil water, plant).

With this general picture of each compartment of a WaterRenew system, it is necessary to understand what proportion of applied nutrients ends up in each of the compartment of a WaterRenew system, i.e. soil, water and plant.

Thus, in a WaterRenew system,

- 1) nutrients are applied by irrigation
- 2) they then can enter one of the following compartments; soil, plant or soil water and can be redistributed between them:
- 3) - if in above ground plant material, then sampling from leaves and stems, and analysis of their nutrient contents and measurements of their yield made possible to assess nutrients uptaken by plants (details in Chapter 4).
 - If in soil compartment, then soil sampling and analysis make it possible to assess the amount of nutrients participating in soil adsorb-desorption dynamic (details in Chapter 5)
 - If in soil water, then, it is more complicated as soil water can enter the system by infiltration into soil pores and leave the system by runoff, subsurface flow or drainage. Hence, to assess this amount, it is necessary to have an idea of the water balance on this site and under different tree species.
- 4) Finally, the balance of the nutrients will be equilibrated to understand the flows between the different compartments soil, plant and soil water. Although it is known that N can be lost by volatilisation (Hellebrand et al., 2008), there was no resource available to study gaseous loss during this field trial.

Therefore, the objective of this chapter is to approach the balance of the nutrients by first proposing a best way to approach a value for drainage by solving the soil water balance, secondly to propose a nutrients budget for a WaterRenew system at the end of 2 years of irrigation with secondary treated effluent, and finally to draw conclusions on the performance or efficiency of a WaterRenew system on Cranfield University field trial on a chalky clayey soil in Bedfordshire, UK.

The specific objectives of this chapter were :

- **Objective 1:** to estimate the water balance for Cranfield WaterRenew system.
- **Objective 2:** to calculate the nutrient balances to assess nutrients fate in the system and to estimate its efficiency or performance.

2. MATERIALS AND METHODS

2.1 SITE

A WaterRenew system was set up at the Cranfield University sewage treatment works (Bedfordshire, UK) in October 2005. The mean annual precipitation was 629 mm; 10.0°C mean annual temperature and an annual average Penman evapotranspiration of 1.4 mm.day⁻¹ (Cranfield University, Silsoe Met Station, data from 1962-2006).

According to Soil Survey of England and Wales soil map (1993), the Cranfield site soil is a slowly permeable chalky clayey soil or Hanslope (NSRI, 2008).

2.2 TREATMENTS

The field was artificially built and the soil completely disturbed. It was divided into 24 plots of 3.5 m by 3.5 m spaced with a 1 m pathway (Figure 2). Each plot was bounded by a polythene sheet of 60 cm width, buried to 50 cm depth to prevent surface runoff or near surface lateral movement. The 24 plots were organised in three replicates randomly distributed, of four covers under two treatments. The covers were: 16 trees of willow (W, *Salix viminalis*), poplar (P, *Populus trichocarpa*), eucalyptus (E, *Eucalyptus gunnii*) at a tree spacing of 1 m, the four inner trees being measurement trees, and an unplanted control, (U). The plots were randomly assigned to be either: irrigated with wastewater (+) or non-irrigated (-) as a control of treatment. Usually, at the end of the first year, mono-stems are cut back to promote sprouting (DEFRA, 2002.). In order to mimic this second year cut back poplars and willows were planted as a cluster of five cuttings in spring 2006.

A computerised drip-irrigation system was set up, with 16 drippers (4 L.hour⁻¹) per plot from July 2006 until August 2007. Then, in August 2007, the irrigative capacity was doubled from 15mm/day to 30mm/day on installing new drippers.

The main concept of the irrigation system settings was to allow the maximum water application whilst avoiding runoff, minimising drainage and consequently creating well watered, favourable conditions for plant growth. For this reason, the irrigation was triggered by soil moisture measurements (soil moisture sensor SM200, Delta T) taken from the middle of each plot to start when soil moisture content is lower than field capacity. The irrigation began in mid-July 2006 and continued until late December 2006. It was then halted by water freezing in the pipe work until late February 2007. The second irrigation period lasted from March 2007 until October 2007, but manual

doses of effluent were added during the 2007-2008 winter, until February 2008 when the trees were harvested.

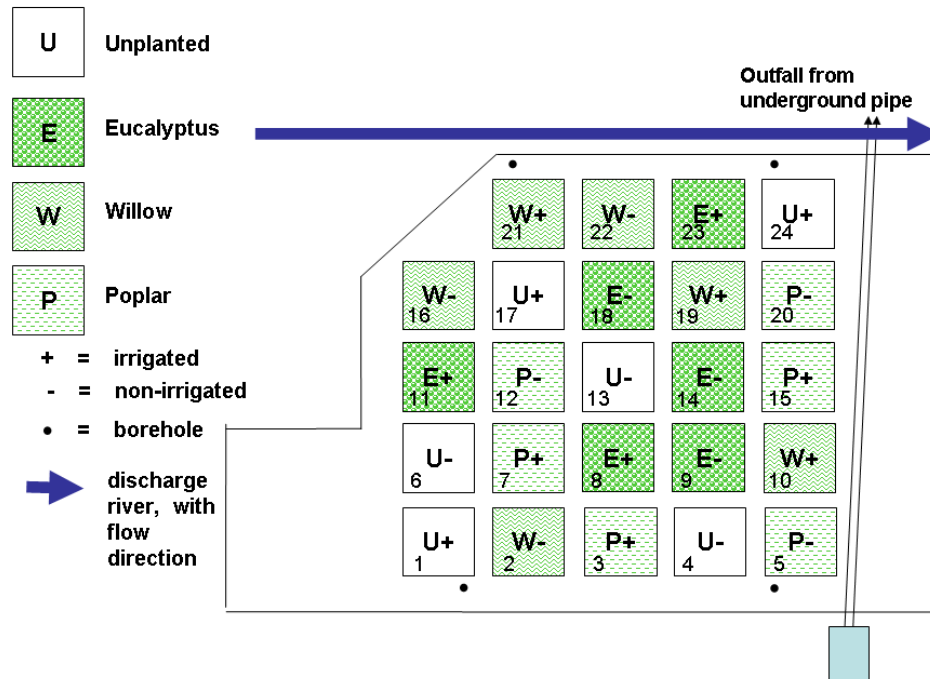


Figure 2 Cranfield site field trial map, localisation of 24 randomly distributed plots, 3 replicates of 4 covers, unplanted, eucalyptus, willow and poplar, irrigated or not.

2.3 SOIL MOISTURE MEASUREMENTS

2.3.1 Theta probes (SM200, Delta-T)

In the middle of each plot, a theta probe (Soil moisture sensor SM200, Delta-T), was installed to measure and record soil moisture every minute in the first 10 cm of soil. The measurements have an accuracy of 3 %, as the probes present a low sensitivity to salinity and an excellent stability to temperature according to the Delta-T SM200 user guide. (Cf. Chapter 3, 5.3)

2.3.2 DIVINER (DIVINER 2000, Sentek sensor technology)

On each plot, a DIVINER access tube was installed to at depth of 1.70 m, where possible. DIVINER data were recorded monthly during the experiment. It is described as “a portable and robust device measuring soil water over multiple depths (at 10 cm

intervals) throughout the profile” (Sentek sensor user guide). It presents 1% volumetric soil water accuracy (Cf. Chapter 3, 6.4)

3. DRAINAGE ASSESSEMENT

One of the main sources of nutrient loss is in soil water when soil water drains out of the system. As it was not possible to directly measure drainage in the field plots, the next step was to assess nutrients balance by calculating a water balance. Therefore, the different elements of the water balance equation (Equation 1, (Allen, 1998.)) needed to be assessed.

Equation 1 Soil water balance and assumptions

$$ET = Irrigation + Rainfall - Runoff - Drainage + Capillary Rise \\ \pm \Delta SubsurfaceFlow \pm \Delta SoilWater$$

Assumptions :

- 1) *ET = Evapotranspiration*
- 2) *Runoff = 0 (controlled with the polythene sheet)*
- 3) *Capillary Rise = 0* $\left(\begin{array}{l} \text{because of lower PSMD during period of} \\ \text{ex periment compared to average} \end{array} \right)$
- 4) *Subsurface Flow = 0 (controlled with the polythene sheet)*

Hence

$$Drainage = Irrigation + Rainfall - ET \pm \Delta SoilWater$$

Returning to Equation 1, the water balance for Cranfield site was simplified with the following assumptions:

- A polythene sheet of 60 cm was buried to 50 cm to hydrologically and physically individualise each plot for 2 purposes: to prevent subsurface flows and lateral flows on the first 50 cm depth and secondly, to prevent surface runoff with the 10 cm sheet above ground.
- Capillary rise depends mainly on ET (Hillel, 1980). For the period of experimentation, July 2006 to February 2008, the average annual PSMD from data collected from 1962 to 2007, was of 1246 ± 79 mm. The average annual PSMD for 2006 and 2007 were respectively 1166 ± 82 mm and 769 ± 44 mm. Therefore, for 2006, the PSMD was equivalent to the 40 years average but 2007 was significantly lower. Moreover, on irrigated plots, irrigation maintained soil moisture at or close to field capacity, which would have limited water movement in that

layer. Hence, even though the water table was high (between 0.8m-1.6 m), capillary rise was considered as limited and not accounted hence forth.

Rainfall and evapotranspiration were measured locally and data are available from Silsoe campus (Cranfield University) automatic meteorological station. Irrigation was also measured on site, with available data. Hence, the only term to be calculated was drainage.

The water balance equation considered is a simplified equation. Drainage approximation or calculation can also be simplified and for this reason, different approaches were considered to calculate drainage, from the simplest crude approach to more sophisticated calculation, using soil moisture and DIVINER data. Thus the different approaches are summarised as follows:

- 1- A crude assessment of drainage with rainfall data only; if the system is maintained at field capacity; i.e. irrigation accounts for losses by ET, then any rainfall occurring would contribute in totality to drainage; hence, rainfall volumes would be a plausible estimate of drainage.
- 2- The assessment of drainage by soil moisture readings at 10 cm depth: data are available every 10 min on each plot. Because of the definition of field capacity (Hillel, 1980), whenever soil moisture measurements were greater than field capacity, the difference to field capacity was assumed to have drained. As the measurements were taken at 10 cm, it was assumed that if water was draining at 10 cm, the same amount would drain at 60 cm. Therefore, these drained volumes were also considered as plausible estimate of drainage.
- 3- The assessment of variation of soil water storage by DIVINER data in order to equilibrate soil water balance and assess drainage. Monthly soil water storage variations were calculated using DIVINER monthly measurements of soil moisture distribution on a profile of 1.7 m. Hence with rainfall, ET and irrigated volumes, it was possible to calculate drainage volume by differences.

3.1 CRUDE ASSESSMENT OF DRAINAGE WITH RAINFALL DATA ONLY

3.1.1 Assessment of the drained volume of soil water

A first assumption for this assessment is that the irrigation never led to drainage as it was set to maintain soil moisture at field capacity. Hence, soil was always at least at field capacity when the irrigation was on. It was also assumed that during winter, or

non-irrigation periods, soil remained at field capacity. This was verified by soil moisture data during winter 2006-2007 when loss of water by evapotranspiration was very limited. Therefore, any rainfall would take soil moisture over field capacity and by definition induce drainage (Hillel, 1980).

During the period between the July 14th 2006, when the irrigation system was turned on, until 31st of December 2007, when it was turned off, soil was at least at field capacity. Therefore, the total amount of rainfall drained was equal to 1071 mm (Table1).

Table 1 Drainage estimated as cumulative total rainfall (1,071 mm), total irrigated amount and proportion of the drained volume to total water applied to the field from 14/07/06 until 31/12/07.

	<i>Willow</i>	<i>Poplar</i>	<i>Eucalyptus</i>	<i>Unplanted</i>
Total rainfall (mm)	1071	1071	1071	1071
Total irrigated amount (mm)	3380	2641	3094	1256
% drainage to total water received	24	29	26	46

3.1.2 Assessment of the leached amounts of nutrients

A simple assessment of the amount of nutrient leached was made by using the crude estimation of volumes of water drained and the averaged nutrients concentration in soil water from both depths of 30 cm and 60 cm over the monitoring period under irrigated plots (Table 2).

However, this simple assessment incurred some errors based on the following assumptions:

- Irrigation does not contribute to drainage, meaning that errors of measurement of $\pm 3\%$ from the theta probes, on which irrigation system is triggered, were not taken in account.
- The totality of rainfall manages to leach out of the 60 cm depth profile, in other words, no loss of rainfall during the infiltration process. Moreover, infiltration is controlled by infiltration rate (Hillel, 1980) and therefore, it is not possible to infiltrate a greater volume during a specified period of time than the infiltration rate, however, this was not taken in account and rainfall rates were not compared to infiltration rates.

- The variability of soil solution chemistry was not taken in account as means were used, even though their chemistries were evaluated to change significantly during the duration of the experiment.

The nutrients concentration used to calculate the amount of nutrients leached out of the system by drainage are summarised in Table 2.

Table 2 Average concentrations of different nutrients in soil water from samples collected fortnightly under irrigated plots for all covers, at 30 and 60 cm depth, from 22/07/06 to 11/02/08

	<i>Number of observa- tion</i>	<i>Mean</i>	<i>Mini- mum</i>	<i>Maxi- mum</i>	<i>Standard Deviation.</i>
Irrigated NH ₄ (mg-N.L ⁻¹)	703	0.38	0	98.4	4.08
Irrigated TON (mg-N.L ⁻¹)	696	5.51	0	113.2	11.92
Irrigated TN (mg-N.L ⁻¹)	712	6.95	0	83.5	12.27
Irrigated plots: PO ₄ (mg-P.L ⁻¹)	686	0.01	0	1.3	0.08
Irrigated plots: TP (mg-P.L ⁻¹)	697	0.04	0	8.28	0.39
Irrigated K (mg-K.L ⁻¹)	682	15.8	0	236.95	27.89
Irrigated Na (mg-Na.L ⁻¹)	441	48.67	0	327.10	44.98

The total amounts of nutrients applied on soil are reported in Table 3. They were calculated by multiplying total irrigated volumes on each cover with average effluent concentrations.

Table 3 Average amount of different nutrients applied by irrigation from 22/07/06 to 11/02/08 under the different covers.

	<i>Willow</i>	<i>Poplar</i>	<i>Eucalyptus</i>	<i>Un- planted</i>	<i>average</i>
Ammonia applied kg.ha ⁻¹	48	37	43	17	36
TN applied kg.ha ⁻¹	1036	808	948	385	794
TON applied kg.ha ⁻¹	858	670	785	319	658
Phosphate applied kg.ha ⁻¹	140	110	129	52	108
TP applied kg.ha ⁻¹	142	112	130	53	109
K applied kg.ha ⁻¹	915	715	838	341	702
Na applied kg.ha ⁻¹	2136	1668	1955	793	1638
mm	3380	2641	3094	1256	2593

Then, the proportions of the amount of nutrients leached were calculated back regarding the total amount applied by irrigation during the whole period of experimentation.

Table 4 Estimated amounts of leached nutrients on using drained volume as total cumulative rainfall for the period 14/07/06 until 31/12/07 and average concentrations for each nutrient over the same period. % of total applied amount of nutrients leaching amounts represent.

	<i>Leached nutrient (kg.ha-1)</i>	<i>% of applied nutrient</i>
Rainfall when plots were irrigated (mm)	1071	
Leached NH ₄ (kg-N.ha-1)	4.1	11.2
Leached TON (kg-N.ha-1)	59	9.4
Leached TN (kg-N.ha-1)	74.4	9.0
Leached PO ₄ (kg-P.ha-1)	0.1	1.0
Leached TP (kg-P.ha-1)	0.4	4.0
Leached K (kg-K.ha-1)	169.2	24.1
Leached Na (kg-Na.ha-1)	521.2	31.8

With this calculation, the estimated amount of nutrient leached remained very low, for example the proportion of TN leached representing 9 %, the proportion of TP leached, 0.4 %, the proportion of K leached, 24.1 % and the proportion of Na applied leached, 31.8 %.

3.2 ASSESSMENT OF DRAINAGE BY THETA PROBE SOIL MOISTURE READING AVERAGED DAILY

3.2.1 Assessment of the drained volume of soil water

The average of soil moisture was measured every minute using theta probes at 10 cm depths and recorded every 15 minutes. These records for each plot were used to calculate drainage. The ensuing steps noted below were followed and are described in Figure 3:

- 1) The daily soil moisture average was calculated for each plot from recorded 15 min averages.
- 2) The average daily soil moisture averaged by replicates was calculated (i.e. eight ones, being the combination of four covers, irrigated or not)

(Standard deviations calculated were lower than the accuracy that Delta-T guaranty on the measurements as 1 % < 3 %)

- 3) These averages were compared to the estimated field capacity value, FC, of 0.55. Indeed, the part of soil moisture greater than FC was taken in account as it would by definition contribute to drainage.
- 4) These differences to FC were converted from % (as volumetric content) to mm on 10 cm depth per m².
- 5) The resulting drainage volumes are presented in Table 5.

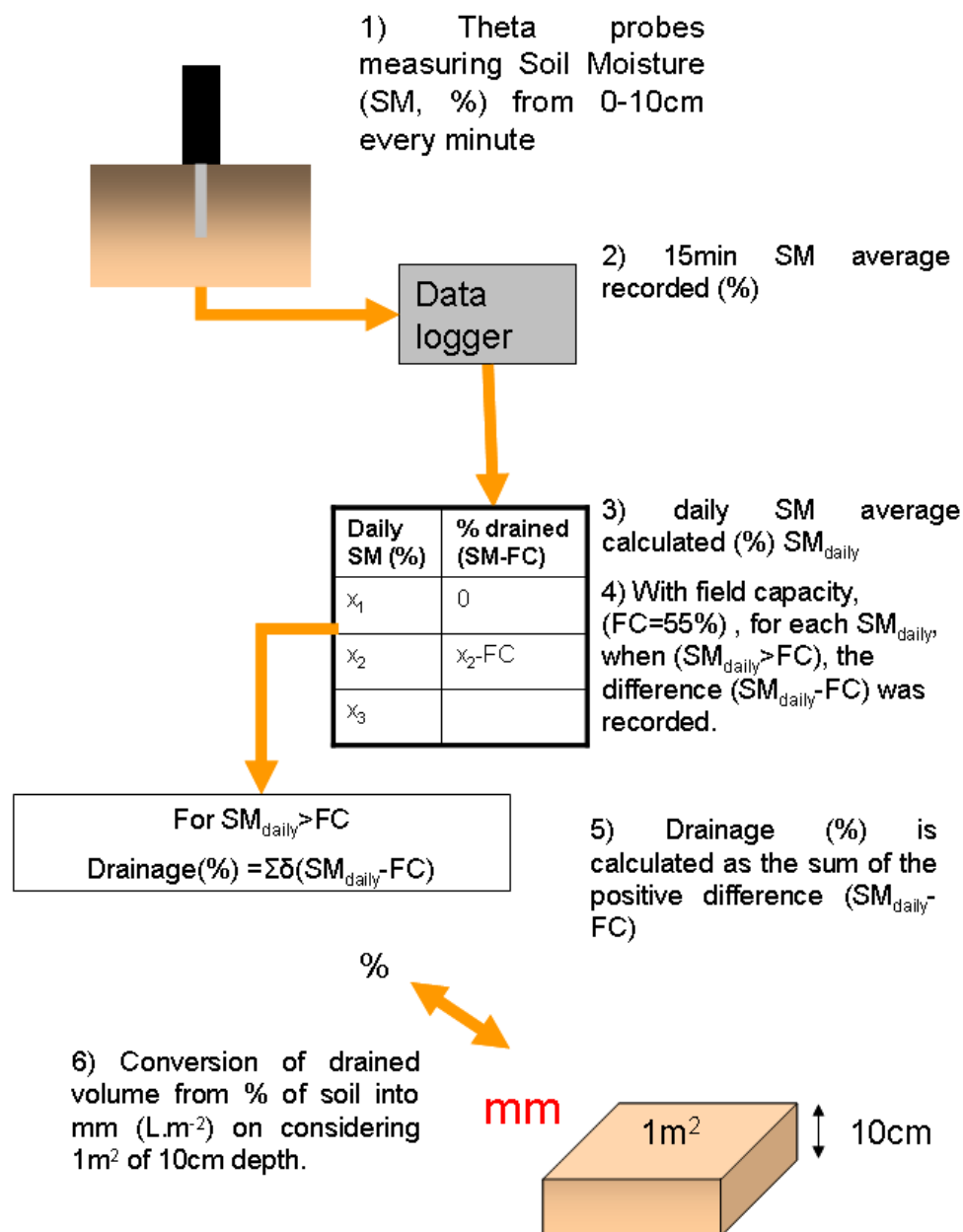


Figure 3 Steps for drainage calculation from the theta probes measurements.

Table 5 Total rainfall, total irrigated amount, total drainage calculated from soil moisture daily averages (% in volume) differences at 10 cm compared to field capacity (0.55) for the period 14/07/06 until 10/02/08.

	<i>Willow</i>	<i>Poplar</i>	<i>Eucalyptus</i>	<i>Unplanted</i>
Total rainfall (mm)	1071	1071	1071	1071
Total irrigated amount (mm)	3380	2641	3094	1256
Total drainage calculated from SM (mm)	248±95	82±78	108±44	212±17
% drainage to total water received	6±2	2±2	3±1	9±1

For all the covers, drained volumes estimates were under 100 %, hence, they are probable values.

However, the weaknesses of this approach will be discussed in the following paragraph in order to judge its suitability for this thesis.

This assessment of drainage did induce some errors based on the following assumptions which are justified by the subsequent statements:

- Soil moisture variation at 10 cm was assumed to be translated at 60 cm, for example if a drainage of x mm occurs from the layer 0-10 cm, it is assumed that it will induce a drainage of x mm at 60 cm. This might not have been true at the beginning of the experiment when soil profile had to be wet up during summer 2006. However, once the system was wet up to field capacity, the whole profile, from surface to 60 cm depth, can be considered as homogeneous and therefore, any soil moisture over field capacity at 10 cm should move out of the profile at 60 cm without any significant loss.
- Soil moisture measured at the centre of the plot by the theta probe was representative of the whole m². This assumption cannot be verified, however, the placement of the probe in the centre of the plot was chosen as it was believed to be the most representative of the entire plot's hydrology.
- Drained volumes were not compared to infiltration or drainage rate; all the volume calculated as drained were assumed to effectively drain even though it might have been impossible hydrologically because it would imply a drainage rate potentially over the field drainage rate (Hillel, 1980). An attempt to measure drainage rate with falling and constant head tests on undisturbed

soil columns (Ward et al., 2004) failed to give reliable drainage rate (the standard deviation of the measurements was greater than the mean)

- There were also some uncertainties over the real field capacity value as well. Field capacity was determined using sand table (Avery et al., 1974.) (Chapter 3, 5.2) and has been assumed equal to 0.55 (%).
- There were also assumptions made on the calculation level: 15 min soil moisture records were averaged over 24 hours to give a unique daily value. Standard deviation for this unique daily value was calculated and compared to the mean. The standard deviation of this averaging was of 1 % (Table 5), hence within the accuracy of SM200 theta probes (SM200 user guide).

3.2.2 Assessment of the leached amount of nutrients by drainage

On combining averages soil water composition (Table 2, 7-9) and drainage volume (Table 5), the amount of nutrients leached by drainage were calculated and are shown in Table 6.

Table 6 Amount of nutrients leached out from the system when drainage is assessed by soil moisture measurements, with field capacity, FC, of 0.55 and a layer of 10 cm of soil considered for the whole period of experiment (July 2006-December 2007).

	<i>Mean</i>			
	<i>Willow</i>	<i>Poplar</i>	<i>Eucalyptus</i>	<i>Unplanted</i>
Drainage (mm) with FC=0.55 on 10 cm layer	248± 95	82± 78	108± 44	212± 17
Leached NH₄ (kg-N.ha-1)	0.9± 0.4	0.3± 0.4	0.4± 0.2	0.8± 0.1
Leached TN (kg-N.ha-1)	17.2± 6.6	5.7± 5.4	7.5± 3.1	14.7± 1.2
Leached TON (kg-N.ha-1)	13.7± 5.2	4.5± 4.3	6.0± 2.4	11.7± 0.9
Leached plots: PO₄ (kg-P.ha-1)	0.0± 0.6	0.0± 0.5	0.0± 0.3	0.0± 0.1
Leached plots: TP (kg-P.ha-1)	0.1± 10.0	0.0± 8.2	0.0± 4.6	0.1± 1.8
Leached K (kg-K.ha-1)	39.2± 8.2	13.0± 6.7	17.1± 3.8	33.5± 1.5
Leached Na (kg-Na.ha-1)	120.7± 46.2	39.9± 38.0	52.6± 21.4	103.2± 8.3

Then, the proportions of the amount leached were calculated back considering the total amount applied by irrigation during the whole period of experimentation.

Table 7 Amount of nutrients leached out from the system when drainage is assessed by soil moisture measurements, with field capacity, FC, of 0.55 and a layer of 10 cm of soil considered.

	Willow	Poplar	Eucalyptus	Unplanted	
Drainage (mm) with FC=0.55 on 10 cm layer	248	82	108	212	<i>average</i>
Leached NH₄ (% of applied)	2.0	0.8	1.0	4.7	<i>2.1</i>
Leached TN (% of applied)	1.7	0.7	0.8	3.8	<i>1.8</i>
Leached TON (% of applied)	1.6	0.7	0.8	3.7	<i>1.7</i>
Leached plots: PO₄ (% of applied)	0.0	0.0	0.0	0.0	<i>0.0</i>
Leached plots: TP (% of applied)	0.1	0.0	0.0	0.2	<i>0.1</i>
Leached K (% of applied)	4.3	1.8	2.0	9.8	<i>4.5</i>
Leached Na (% of applied)	5.7	2.4	2.7	13.0	<i>6.0</i>

Thus, with this calculation, TN leaching was of 1.8 % of the total amount applied, TP of 0.1 %, K of 4.5 % and Na of 6 %.

3.3 ASSESSMENT OF DRAINAGE BY DIVINER DATA AND MET DATA

3.3.1 Assessment of the drained volume of soil water

Drainage can be calculated by balancing a soil water equation (Equation 2).

Equation 2 Soil water balance and assumptions

$$\text{Drainage} = \text{Irrigation} + \text{Rainfall} - \text{ET} \pm \Delta\text{SoilWater}$$

Irrigation: from datalogger

Rainfall – ET: from Silsoe met station data

ΔSoilWater: from DIVINER data

3.3.1.1 Variation in water storage

The Diviner probe is a capacitance probe that takes soil moisture volumetric data every 10 cm. The Diviner data were computed to calculate water storage from surface to 60 cm depths as explained in Figure 4. 26 measurements were gathered between June 2006 and February 2008.

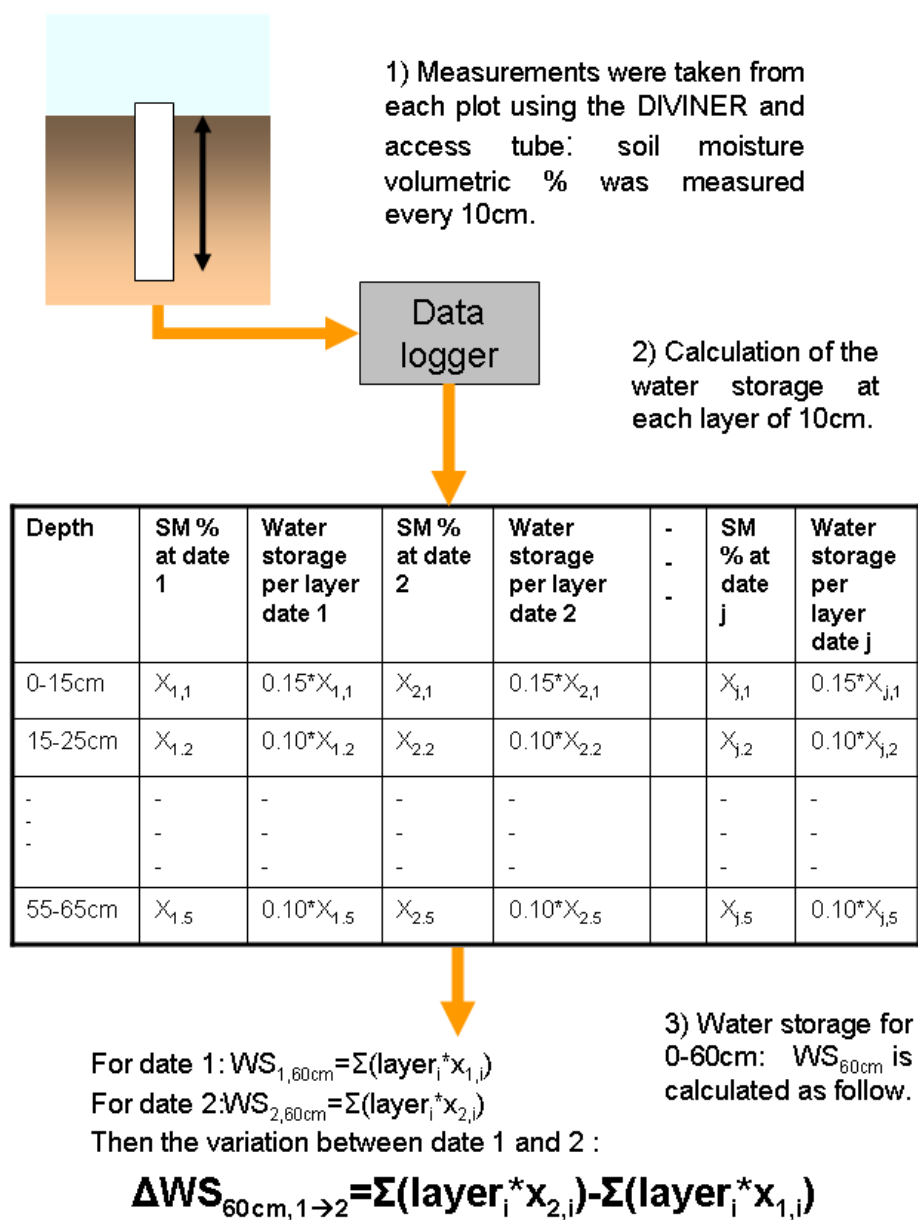


Figure 4 Steps followed to calculate water storage from DIVINER data.

3.3.1.2 Water balance equilibration and drainage calculation

The ET or evapotranspiration calculations are detailed in Chapter 4 (2.4), in particular how water use or Transpiration were calculated for each tree. These are shown in Equation 3 and 4.

$$ET = Tr + Ev$$

Definition

ET : Evapotranspiration ($mm.day^{-1}$)

Equation 3

Tr : amount of water transpiration by crop ($mm.day^{-1}$)

Ev : amount of water evaporation by soil surface ($mm.day^{-1}$)

The transpiration part of ET was identified as water use. Therefore, on considering Equation 3 for both planted and unplanted plots, water uses of different species were assessed as:

$$\Delta Drainage_{Tree-Unplanted} = \Delta Irrigation_{Tree-Unplanted} + \Delta ET_{Tree-Unplanted} \\ \pm \Delta SoilWaterStorage_{Tree-Unplanted}$$

with the simplifications

$$\begin{cases} \text{simplicaiton 1 : } \Delta Drainage_{Tree-Unplanted} \approx 0 \\ \text{simplicaiton 2 : } \Delta SoilWaterStorage_{Tree-Unplanted} \approx 0 \end{cases}$$

Equation 4

hence

$$WaterUse = Tr = \Delta Irrigation_{Tree-Unplanted}$$

Results of these calculations are presented in Table 8.

Table 8 Total rainfall, total irrigated amount, total drainage calculated from water balance with DIVINER data averages for the period 14/07/06 until 10/02/08.

		Total rainfall (mm)	Total irrigation (mm)	DIVINER data Drainage	% drainage to total water received
Willow	Non-irrigated	1071	0	-27	-3
	Irrigated	1071	3380	1893	43
Poplar	Non-irrigated	1071	0	-146	-14
	Irrigated	1071	2641	1418	38
Eucalyptus	Non-irrigated	1071	0	-6	-1
	Irrigated	1071	3094	1719	41
Unplanted	Non-irrigated	1071	0	29	3
	Irrigated	1071	1256	294	13

The drainage data calculated with the DIVINER data are giving negative values for non-irrigated planted plots. This means that according to these calculations, the system is losing more water than it is receiving for tree planted non-irrigated plots, that is to say the system is drying up.

According to Equation 2, the system can lose water either by ET or drainage. Moreover, the main uncertainty for drainage calculation is linked with uncertainties for water use estimations. Hence, the system may have been be transpiring too much if the estimations are considered. In addition, it also revealed that for irrigated plots, it seems that an increase in effluent irrigation leads to increased drainage. This is also due to the uncertainties of water use estimates, as they were calculated as the difference between irrigated volumes on planted plots and unplanted plots (Equation 4, Chapter 4, 2.4).

Therefore, ET was calculated using crop coefficient available for willow from the literature (Jørgensen and Endorichio, 2001; Jorgensen and Schelde, 2001) Table 9. However, these K_c are lower than the Cranfield calculated K_c . K_c from in Chapter 4 (section 3.3.3) were calculated using T_r and ET_0 data from the field, therefore, they could not be used to calculate ET.

Table 9 K_c for willow during the 3 years for SRC Adapted from (Jorgensen and Schelde, 2001) and drainage volumes calculated with these K_c for willow.

<i>Month</i>	<i>Year 1</i>	<i>Year 2</i>	<i>Year 3</i>
January	0	0	0
February	0	0	0
March	0	0	0
April	0.6	0.7	0.75
May	0.8	1	0.9
June	1.26	1.1	1.1
July	1.13	1.3	1.25
August	1.45	1.25	1.25
September	1.7	1.1	1.1
October	1.6	1.2	1.5
November	0	0	0
December	0	0	0
Drained volume under Irrigated willow (mm)	2884		
Drained volume under Non-irrigated willow (mm)	1		

For irrigated willow, the drained volume calculated was 1.52 times greater than with previous estimation of K_c . Hence, less evapotranspiration (smaller K_c) resulted in more

drainage. Therefore, it was concluded that Cranfield data based estimations were more accurate even though they were not satisfactory.

3.3.2 Assessment of amounts of nutrients leached.

From Chapter 7, concentrations of ammonia, TN, K and Na in soil solution varied significantly during the monitoring period and under the different covers. Hence to take in account these significant variations in the calculation of the amount of nutrients leached, the concentrations used were the ones measured at the two closest dates to the date corresponding to the drained volume calculation. Total leached nutrients in $\text{kg}\cdot\text{ha}^{-1}$ are presented in Table 10 and the percentage of total applied nutrients they represent are also reported.

Table 10 Estimated amounts of leached nutrients on using drained volume as result from water balance and DIVINER data and averaged concentrations for each nutrient for the closest date of sampling and DIVINER measurement. Amount of the total amount of nutrients applied effectively leached (%).

<i>Tree</i>	<i>Willow</i>	<i>Poplar</i>	<i>Eucalyptus</i>	<i>Unplanted</i>	<i>average</i>
Leached NH_4 ($\text{kg}\cdot\text{N}\cdot\text{ha}^{-1}$)	7.2	5.4	6.5	1.1	5
% NH_4 leached/applied	15	14.6	15.2	6.6	13
Leached TN ($\text{kg}\cdot\text{N}\cdot\text{ha}^{-1}$)	131.5	98.6	119.5	20.4	93
% TN leached/applied	12.7	12.2	12.6	5.3	11
Leached TON ($\text{kg}\cdot\text{N}\cdot\text{ha}^{-1}$)	104.3	78.1	94.7	16.2	73
% TON leached/applied	12.2	11.7	12.1	5.1	10
Leached PO_4 ($\text{kg}\cdot\text{P}\cdot\text{ha}^{-1}$)	0.2	0.1	0.2	0	0
% PO_4 leached/applied	0.1	0.1	0.1	0.1	0
Leached TP ($\text{kg}\cdot\text{P}\cdot\text{ha}^{-1}$)	0.8	0.6	0.7	0.1	1
% TP leached/applied	0.5	0.5	0.5	0.2	0
Leached K ($\text{kg}\cdot\text{K}\cdot\text{ha}^{-1}$)	299	224.1	271.6	46.4	210
% K leached/applied	32.7	31.3	32.4	13.6	28
Leached Na ($\text{kg}\cdot\text{Na}\cdot\text{ha}^{-1}$)	921	690.2	836.6	143	648
% Na leached/applied	43.1	41.4	42.8	18	36

For TN, the amount leached represents an average of 13 %, 0 % for TP, 28 % for K and 36 % for Na of the total applied.

3.4 COMPARISON OF THE AMOUNT OF NUTRIENTS LEACHED UNDER THE DIFFERENT COVERS ACCORDING TO THE DIFFERENT CALCULATIONS OF DRAINAGE

In order to try to select the better approach in terms of assessing the amount of drainage which took place during the whole time of experiment, the different results obtained by the different method are compared in Table 11.

Table 11 Relative comparisons of the different amounts of drainage calculated with the different methods. Rainfall: the simple rainfall assessment, SM: the approach with soil moisture probes data, DIVINER: the approach with DIVINER data.

	<i>Willow</i>	<i>Poplar</i>	<i>Eucalyptus</i>	<i>Unplanted</i>
Rainfall estimated drainage (mm)	1071	1071	1071	1071
DIVINER data Drainage (mm)	1893	1418	1719	294
Soil moisture estimated drainage (mm)	248	82	108	212
DIVINER/Rainfall estimated	1.77	1.32	1.61	0.27
DIVINER/Soil moisture estimated	7.63	17.30	15.92	1.39
Rainfall estimated/Soil moisture estimated	4.32	13.06	9.92	5.05

For the three approaches, drainages under the different covers were classified in the same order. Indeed, for the 3 of them, the amount drained is in the same order than the amount irrigated. Hence it means the more plots were irrigated, the more they were draining. This would be logical only if plots were irrigated over field capacity. Therefore, the data suggest that field capacity was overestimated and was probably lower than the estimated 55 % volumetric water content.

As drainage has probably been induced in this experiment and as the DIVINER approach calculated the greatest amount of drainage, it would represent the greatest amounts of nutrients leached. For this reason, it will represent the “worst” case scenario and will be considered to calculate nutrients balance.

4. TOTAL BALANCE USING DRAINAGE CALCULATED WITH DIVINER DATA

The amount of nutrients applied was calculated based on irrigated volumes recorded with the irrigation system set up in Cranfield University. The different amounts of nutrients uptaken in trees were assessed in Chapter 4. The variation in the nutrients’

stock in soil was measured in Chapter 5 and the evolution of the nutrients' concentrations in soil water were discussed and presented in Chapter 6 (Figure 5).

As the nutrients' content of tree biomass was measured as TN, TP and TK, the balances of these forms will be assessed.

N, P, K, Na cycle considered

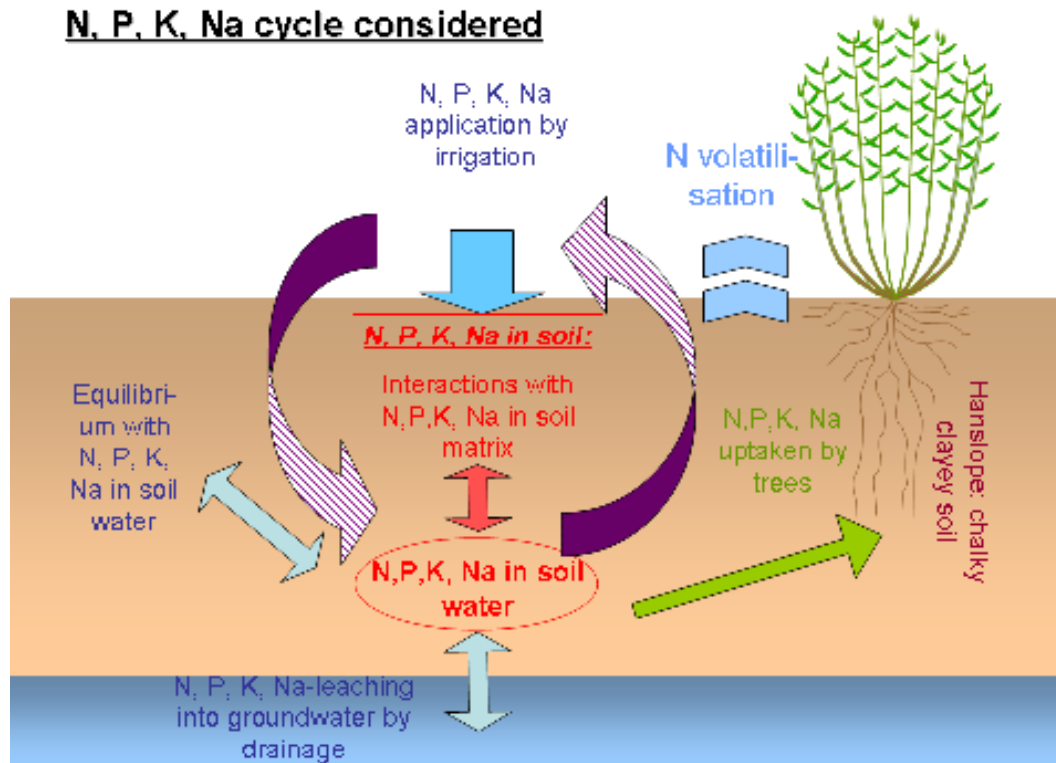


Figure 5 Components considered to establish N, P, K and Na balances.

4.1 TOTAL NITROGEN BALANCE AND N FATE

The fate of N applied is presented in Figure 6 to assess the performance of the different trees for N removal by integrating data from Chapter 4 (nutrients uptake, section 3.4.1), Chapter 5 (amounts of N applied and mineral N variation in soil, sections 3.1.1 and 3.8) and Chapter 6 (N evolution in soil water, section 3.3). The relative proportions of N uptakes, N lost by drainage were drawn by considering the amount of N applied as 100 %. According to Chapter 5, the evolution of TN in soil was not significant. Therefore, the difference between the total amount of P applied and the sum of P uptaken and lost by drainage, could not be considered precisely as accumulating in soil and was thus classified under unknown fate.

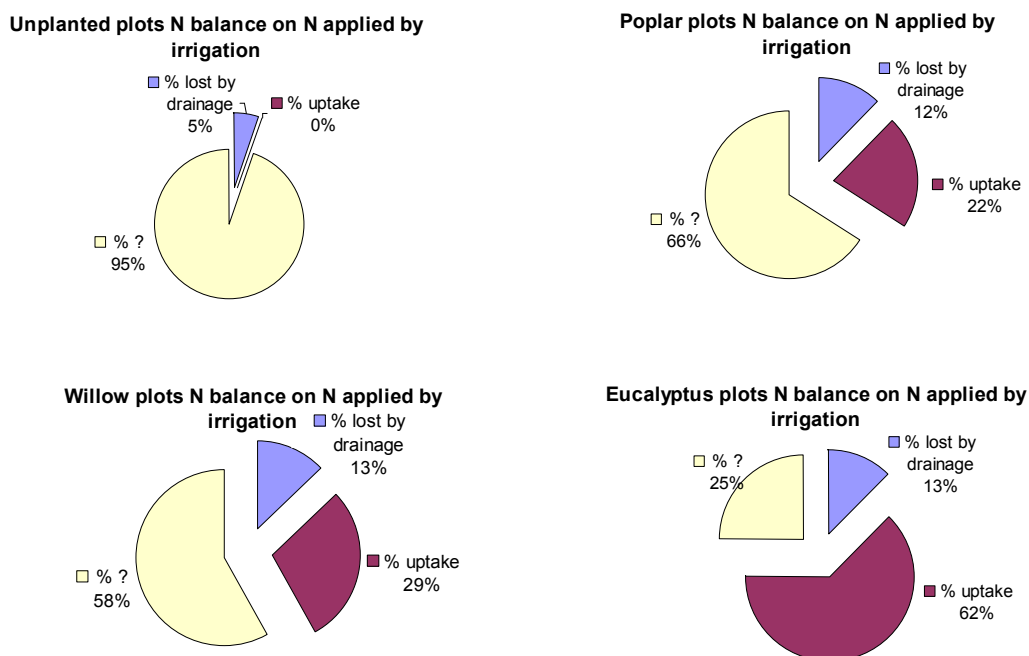


Figure 6 Applied N fate in plots with different covers (unplanted, planted with willow, poplar or eucalyptus) irrigated or not after 2years of experimentation (July 2006 – February 2008) TN in soil was not presented as it was assumed there was no change in soil N store.

For unplanted plots, the majority (95 %) of total N applied volatilised or remained in the system, probably by immobilisation in soil organic matter. When comparing the different trees, eucalyptus appeared to be the best tree with comparable N leaching (13 %), the comparative amount uptaken were greater than for willow and poplar (62 %, 22 % and 29 % respectively) when the totality of biomass produced was

accounted (leaf+ wood+ roots). Moreover, as eucalyptus does not lose its leaves during autumn, the N uptake is definitive once trees were harvested.

As noted in Chapter 5 (3.8.2), the TN in soil did not change significantly with time, moreover, the variability of soil TN was greater than the values for TN applied by irrigation, uptaken by trees or leached by drainage; that is the error bars for soil TN variations were greater than the other numbers (Table 12).

Table 12 Components of TN balance expressed in t.ha^{-1} , TN applied by irrigation, TN variation in soil profile from 0-60 cm and SD: standard deviation, TN uptaken by plant (leaf, stem and roots), TN lost by drainage calculated with the DIVINER approach, over the period of experiment from the 14/07/06 until the 11/02/08.

Tree	Unplanted	Willow	Poplar	Eucalyptus
TN applied (t.ha^{-1})	0.385	1.036	0.808	0.948
TN uptaken* (t.ha^{-1})	0.000	-0.302	-0.178	-0.591
$\Delta\text{TN}_{0-60\text{cm}}$ (t.ha^{-1})	1.930	-5.539	3.472	2.958
SD $\Delta\text{TN}_{0-60\text{cm}}$ (t.ha^{-1})	3.343	2.105	6.738	5.891
$\Delta\text{NH}_4_{0-60\text{cm}}$ (t.ha^{-1})	0.003	0.017	0.015	0.023
$\Delta\text{TON}_{0-60\text{cm}}$ (t.ha^{-1})	-0.020	-0.046	-0.008	-0.039
$\Delta\text{N}_{\text{mineral}_{0-60\text{cm}}}$ (t.ha^{-1})	-0.017	-0.029	0.008	-0.016
TN lost from Soil Water (t.ha^{-1})	-0.020	-0.132	-0.099	-0.119

*TN uptaken by leaf, wood and roots ; $\Delta\text{TN}_{0-60\text{cm}}$, total variation of TN in soil from 0-60 cm (t.ha^{-1}); $\Delta\text{NH}_4_{0-60\text{cm}}$ Total variation of NH_4 in soil from 0-60 cm (t.ha^{-1}) ; $\Delta\text{TON}_{0-60\text{cm}}$ Total variation of TON in soil from 0-60 cm (t.ha^{-1}) ; $\Delta\text{N}_{\text{mineral}_{0-60\text{cm}}}$ Total variation of Mineral-N in soil from 0-60 cm (t.ha^{-1})

According to Table 12, the TN variations in soil were the most important variation (over 200 % to 900 % of the total applied TN by irrigation). In particular, the TN leached in drainage (maximum of 13 % of total applied TN) or the TN uptaken by trees (maximum of 62 % of total applied TN) were amounts of same degree of magnitude than applied TN.

Hence, it means that for the short periods of time considered, the amount of TN added, uptaken or leached by drainage were not significant compared to the amount of TN already present in soil. For this reason, variations of TN in soil were not considered further in the balance.

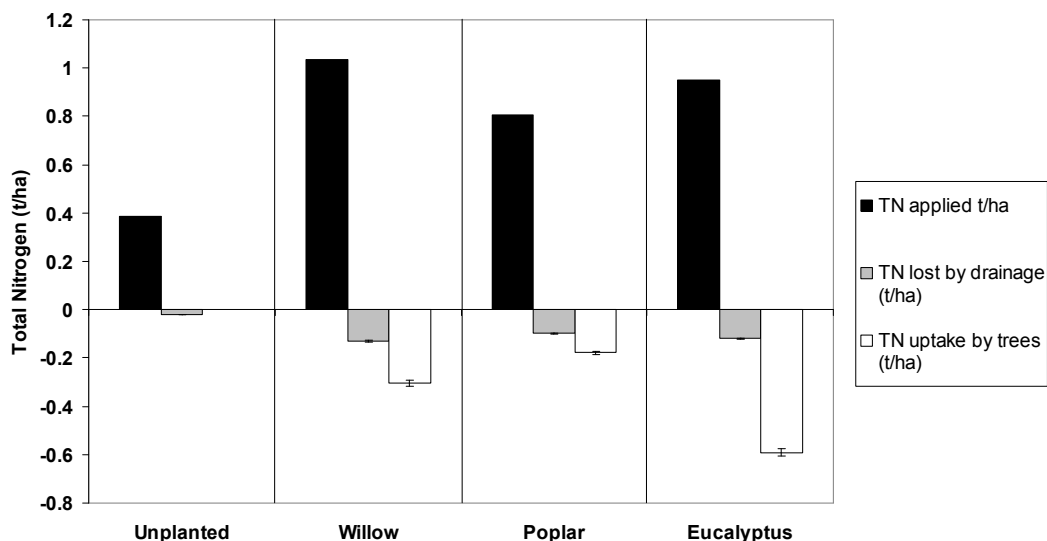


Figure 7 TN total balances in $\text{t}\cdot\text{ha}^{-1}$ with TN applied, TN variation in soil from the beginning of the trial to the end, for a layer of 60 cm, TN leached with soil water, TN uptake by trees after 3 years and TN in soil was not presented as it was assumed there was no change in soil N store. (Vertical bars denote 0.95 confidence interval)

The amounts of N applied by irrigation were much greater than standard amounts applied to fertilise soil. Usually, N-fertilisation is around $250 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ (MAFF 2000), therefore the amounts applied during this experiment were 3 to 4 times greater (Table 12). This N applied can either be solubilised in soil water solution, uptaken by plant, become part of soil matrix by organic incorporation, or be volatilised in the air (Figure 7). Therefore, relative proportions of N in each of these compartments are discussed in the following paragraphs.

First of all, there were great uncertainties about the determinations of N in each of the compartment where it was measured (soil, plant, soil water).

- Proportion of applied N uptaken by plants:

Amounts uptaken by trees were between 22 % and 62 % of applied N when leaf, wood and roots biomass were considered together. These percentages were comparable to Aronsson study (Aronsson and Bergstrom, 2001) where 57 % of the total N applied on a clay soil ($464 \text{ kg}\cdot\text{ha}^{-1}$) were uptaken by 2 years old willow trees cultivated in lysimeters.

- Proportion of applied N leached by drainage:

Despite these great amounts applied, the amount of N leached in soil water also remained low (12 % in average). Aronsson reported greater N leaching happening during the first year (200 % of N applied leaching during the first year) than for subsequent years (37 % for the second year and 3.7 % for the third year with comparable drained volume). High N leaching during the first year is something common as reported in (DEFRA, 2002.) when first year fertilisation is not recommended either. However, for Cranfield site, this phenomenon was not observed. Soil water compositions were discussed in Chapter 6 and in particular, even though TN concentrations varied significantly with time, they were not affected by irrigation (Chapter 6, 3.3.1.3). In addition, they did not vary enough, $TN_{\text{irrigated}} 6.95 \pm 12.27 \text{ mg-N.L}^{-1}$, to induce a 10 times difference between Year 1 (July 2006- March 2007) and Year 2 (March 2007 and February 2008). In particular, at Cranfield site, there was no preliminary high N leaching happening during the first year.

- Proportion of applied N incorporated in soil matrix:

Applied N amounts remained small compared to N variation in soil. N variation in soil was not affected by irrigation (Chapter 5, 3.8). Hence, N applied by irrigation may have contributed to the variation of N in soil, but not significantly.

Mineral-N (total oxidised nitrogen + ammonia) evolution was also reported in Table 12 (details, Chapter 5, 3.8.1). Mineral-N evolutions were of the same order of magnitude than the TN applied, uptaken or leached. There was a net consumption of mineral-N (from 16 kg.ha^{-1} to 29 kg.ha^{-1}) for tree planted plots but a net increase for unplanted plots ($+8 \text{ kg.ha}^{-1}$). But as the TN variations were positive, apart for willow, and not significant, this reflects the fact that mineral-N represents a very little proportion of soil N pool (100 times smaller). There was an incorporation of N in soil organic pool. This is also defined as N immobilisation (Rowell, 1994) "the converse of mineral-N to organic-N". However, this immobilisation was not significant.

- Proportion of applied N lost by volatilisation:

Gaseous losses of N can be a volatilisation of ammonia or nitrous oxides (Rowell, 1994). Nitrous oxides are classified as one of the major greenhouse gases (Houghton and Intergovernmental Panel, 1997). Despite the potential threat for the environment that these gases represent, they were not measured during Cranfield field trial.

(Hellebrand et al., 2008) reported that "water-filled pore space correlates negatively

with N₂O emissions". Moreover, denitrification takes place under anaerobic conditions (Rowell, 1994). During the experiment in Cranfield, the weather was wetter than the last 30 years average (Chapter 4, 3.1) and irrigation was maintaining soil moisture at 55 % (volumetric soil moisture). Therefore, favourable conditions for denitrification and therefore volatilisation of nitrous oxide were gathered. Hence, a proportion of applied TN might have been lost by volatilisation but this loss cannot be quantified. However, an average value is proposed in the literature, that between 0.01- 2 % of the total applied mineral N would be lost in average by volatilisation (Conrad et al., 1983)

As the TN pool in soil is very big and N volatilised cannot be measured, it is very difficult to quantify precisely N movement. One way to quantify more precisely N movement, would be to use the stable isotope of N, ¹⁵N (Liu et al., 2006) and mark N applied by fertilisation and follow its concentrations in soil, tree and soil water.

4.2 TOTAL PHOSPHORUS BALANCE AND P FATE

The fate of P applied is presented in Figure 8 to assess performance of the different trees for P removal on integrating data from Chapter 4 (nutrients uptake, section 3.4.1), 5 (amounts of P applied and Olsen-P, TP variations in soil, sections 3.1.2 and 3.9) and 6 (P evolution in soil water, section 3.2). The relative proportions of P uptakes and P lost by drainage were drawn when considering the amount of P applied as 100 %. According to Chapter 5, the evolution of TP in soil was significant and therefore, the difference between the total amount of P applied and the sum of P uptaken and lost by drainage was classified under unknown fate and will be examined in more details in the following sections.

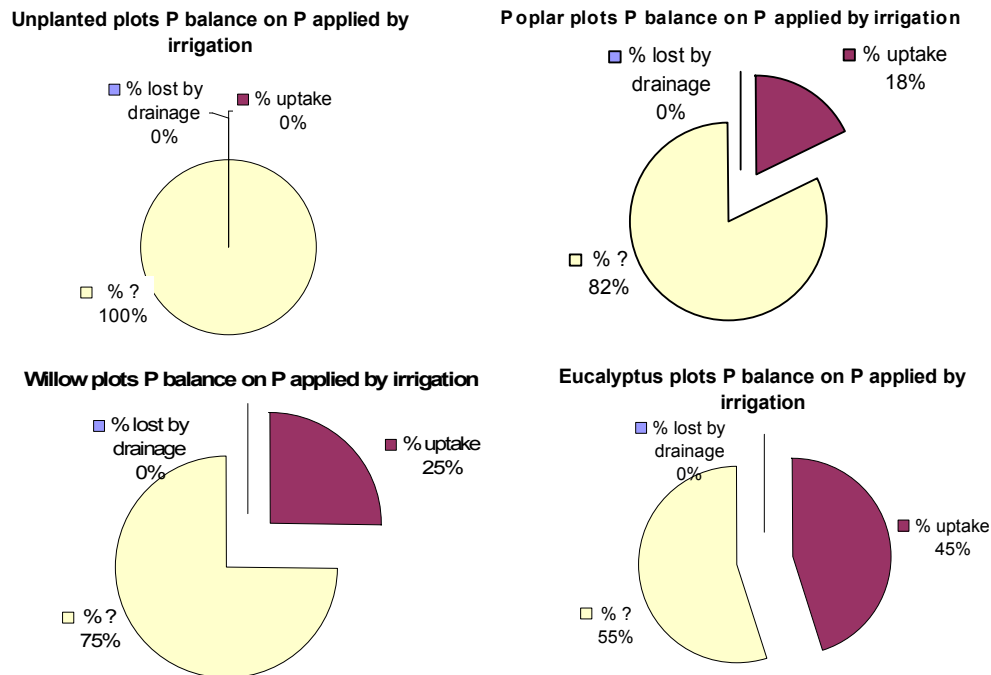


Figure 8 Applied P fate in plots with different covers (unplanted, planted with willow, poplar or eucalyptus) irrigated or not after 2years of experimentation (July 2006 – February 2008)

The magnitude of total phosphorus, TP, changes in soil, and its variability (standard deviation $> 700 \text{ t.ha}^{-1}$) were very high compared to the amount of P applied ($>100 \text{ kg.ha}^{-1}$), uptaken ($<100 \text{ kg.ha}^{-1}$) or leached (around 100 kg.ha^{-1}). They were from very different orders of magnitude (Table 13, Figure 9).

Table 13 Components of Total Phosphorus, TP balance expressed in t.ha⁻¹, TP applied by irrigation, TP variation in soil profile from 0-60 cm and SD: standard deviation, Olsen-P variation in soil profile from 0-60 cm and SD: standard deviation, TP uptake by plant (leaf, stem and roots), TN lost by drainage calculated with the DIVINER approach, over the period of experiment from the 14/07/06 until the 11/02/08.

Tree	Unplanted	Willow	Poplar	Eucalyptus
TP applied (kg.ha ⁻¹)	53	142	112	130
TP uptake* (kg.ha ⁻¹)	0	-36	-20	-59
ΔTP_{0-60cm} (kg.ha ⁻¹)	753	779	1233	618
SD ΔTP_{0-60cm} (t.kg.ha ⁻¹)	9628	141	777	1390
$\Delta Olsen_P_{0-60cm}$ (t.ha ⁻¹)	0.120	-0.060	0.109	0.065
SD $\Delta Olsen_P_{0-60cm}$ (t.ha ⁻¹)	0.009	0.075	0.038	0.099
TP lost from Soil Water (kg.ha ⁻¹)	0	0	0	0

*TP uptake by leaf, wood and roots ; ΔTP_{0-60cm} , total variation of TP in soil from 0-60 cm (t.ha⁻¹); $\Delta Olsen_P_{0-60cm}$ Total variation of Olsen-P in soil from 0-60 cm (t.ha⁻¹)

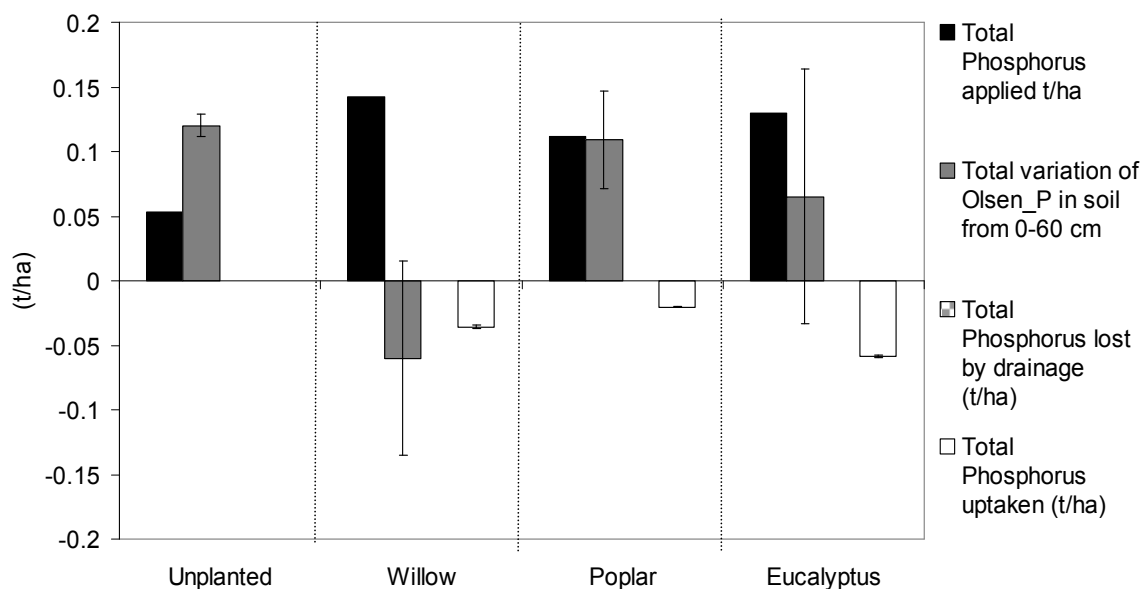


Figure 9 Total Phosphorus, TP, total balances in t.ha⁻¹ with TP applied, total variation of Olsen-P from 0-60 cm profile, TP leached with soil water, TP uptake by trees after 3 years. (vertical bars denote 0.95 confidence interval)

However, the amounts of Olsen-P (>100 kg.ha⁻¹) in the soil were of the same order of magnitude than TP applied, uptake and leached, therefore, they were presented together in Figure 8. A priori, according to Chapter 3 (2.3.2), Olsen-P in soil was initially equal to 22 mg.kg⁻¹, i.e. under Heckrath threshold of 60 mg.kg⁻¹ (Heckrath et al., 1995) therefore, P leaching was not expected for a while.

According to Chapter 5 (3.9.2), TP increased significantly from year to year in soil. However, on comparing the amount applied and the variation of TP in soil, TP application by irrigation cannot explain this increase: the TP variation was over 88,000 times greater than the TP applied (Table 13). The increase in TP in soil may be the result of Na addition and increased solubilisation of P in soil. Even though aqua regia TP was measured, this measurement doesn't account for all TP in soil (Sommers and Nelson, 1972). There are different pools of P adsorbed or fixed or precipitated on soil inorganic matter, with different strength of links with soil matrix. Aqua regia digestion is one method to assess TP in soil (MAFF, 1986.). However, to account for the "real" TP, an acid digestion is not enough and Na_2CO_3 fusion is necessary (Sommers and Nelson, 1972), as showed in Figure 10. Moreover, Sharpley (Sharpley et al., 1988) showed a release in both sorbed-P and dissolution of Ca-P compounds when indigenous cations were replaced by Na and Na saturation was reached.

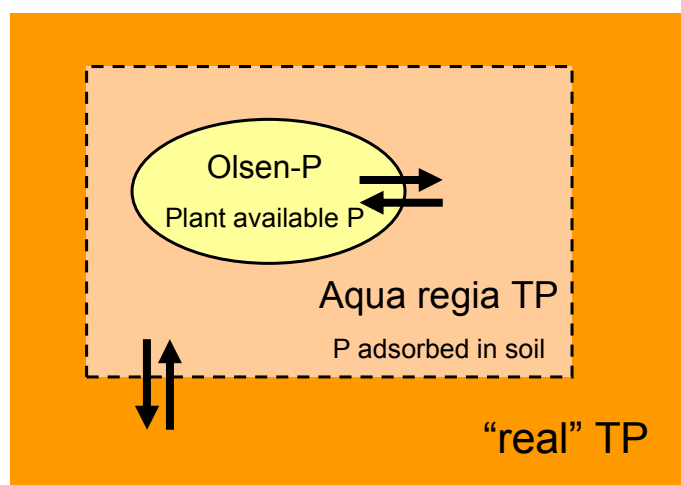


Figure 10 Conceptual model on adsorbed P in soil, interaction between "real" total phosphorus (TP), Aqua regia TP and Olsen-P.

Unlike TN, the amount of TP applied was of the same order of magnitude as TP uptake (three times more for willow, five times for poplar and twice for eucalyptus). And most importantly, there was no P detectable in soil water. Hence P applied went either into the soil, inorganic and organic matter, or into the trees. TP measurements in soil reflect variations in soil organic and soil inorganic P whereas Olsen-P measurements reflect only soil inorganic, readily available adsorbed P (Pierzynski, 2000).

The patterns of variation between the different pools of P were different for the different covers. For unplanted plots, Olsen-P increase was twice the amount of P

applied by irrigation. Hence, applied P contributed to some extent to surface adsorbed P onto soil inorganic matter.

For willow planted plots, the variation of Olsen-P was negative, meaning a consumption of Olsen-P. Olsen-P and tree uptake amounts were comparable. Hence for willow, it seems as if the applied P did not contribute to Olsen-P but to soil organic P pool. As there was net consumption of Olsen-P, it appears that irrigation combined with willow roots presence, enhanced micro organic activities as TP increased.

As for poplar and eucalyptus, P application by irrigation increased Olsen-P pool and the sum of Olsen-P increased, and P uptake by trees is comparable to the amount of P applied. For poplar, there was $14 \text{ kg} \cdot \text{ha}^{-1}$ more in Olsen-P tree uptake pool than applied. Hence, as there was no P detectable in soil water, this additional P was probably resulting from mineralisation of P from soil organic matter to Olsen-P pool (Pierzynski, 2000). For eucalyptus, the opposite happened, there were $16 \text{ kg} \cdot \text{ha}^{-1}$ missing in Olsen-P tree uptake pool than applied, this applied P was probably immobilised into soil organic matter (Pierzynski, 2000).

To conclude on efficiency or performance of the different covers for P removal or transformation, the fact that there was no P detectable in soil water revealed the importance of soil in P processes as even under unplanted plots, there was no P detectable in soil water.

Thus, in terms of the tree species' relative performances, willow appeared to be the best performing. Even though in net amount uptaken, the willow trees took up less than the eucalyptus trees ($36 \text{ kg} \cdot \text{ha}^{-1}$ against $59 \text{ kg} \cdot \text{ha}^{-1}$), willow was the only cover to induce a net decrease in soil Olsen-P pool. In effect, a low value of Olsen-P in soil, reduces the risk of P leaching (Heckrath et al., 1995). Therefore, the willow trees or roots appeared to have an effect on soil organic matter by enhancing P immobilisation into organic matter.

4.3 TOTAL POTASSIUM BALANCE AND K FATE

The fate of K applied is presented in Figure 11 to assess performance of the different trees for P removal on integrating data from Chapter 4 (nutrients uptake, section 3.4.1), Chapter 5 (amounts of K applied and available K, TK variations in soil, sections 3.1.3 and 3.10) and Chapter 6 (K evolution in soil water, section 3.4). The relative proportions of K uptakes, and K lost by drainage were drawn when considering the amount of K applied as 100 %. According to Chapter 5, the evolution of TK in soil was not significant and therefore, the difference between the total amount of K applied and the sum of K uptaken and lost by drainage, could not be calculated precisely as accumulating in soil and was thus classified under unknown fate.

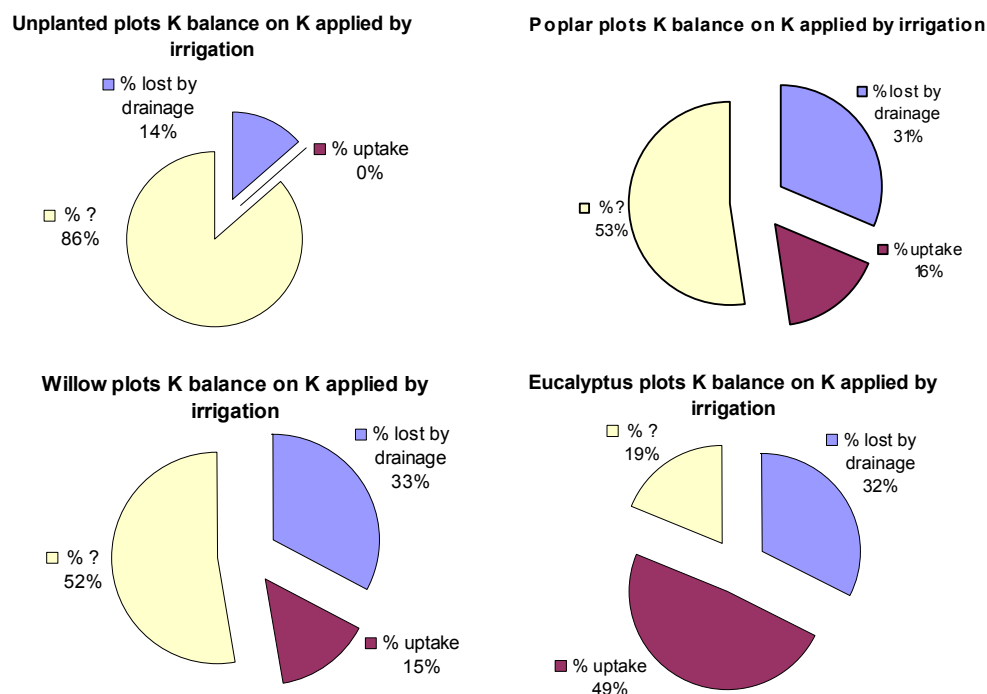


Figure 11 Applied K fate in plots with different covers (unplanted, planted with willow, poplar or eucalyptus) irrigated or not after 2years of experimentation (July 2006 – February 2008)

Export of total potassium, TK, from soil is two orders of magnitude greater than the amounts of TK applied, leached with soil water or uptaken by trees (Table 14). Moreover, standard deviations or variability of soil TK were of the same order of

magnitude than TK variations themselves, i.e. hundred times greater than TK applied, uptaken or leached.

For this reason, instead of presenting TK for soil, available K amounts in soil were considered and presented together with TK applied, leached and uptaken in Figure 12.

Table 14 TK balance expressed in t.ha^{-1} , TK applied by irrigation, TK variation in soil profile from 0-60 cm and SD: standard deviation, TK uptaken by plant (stem and roots), TK lost by drainage calculated with the DIVINER approach, over the period of experiment from the 14/07/06 until the 11/02/08.

<i>Tree</i>	<i>Unplanted</i>	<i>Willow</i>	<i>Poplar</i>	<i>Eucalyptus</i>
TK applied (t.ha^{-1})	0.341	0.915	0.715	0.838
TK uptaken* (t.ha^{-1})	0	-0.13	-0.11	-0.41
$\Delta\text{TK}_{0-60\text{cm}}$ (t.ha^{-1})	-43.02	-30.54	-33.43	-43.26
SD $\Delta\text{TK}_{0-60\text{cm}}$ (t.ha^{-1})	-38.96	-49.34	-33.86	-42.81
$\Delta\text{K}_{\text{av}_0-60\text{cm}}$ (t.ha^{-1})	1.085	0.194	0.637	0.754
SD $\Delta\text{K}_{\text{av}_0-60\text{cm}}$ (t.ha^{-1})	0.655	0.635	0.235	0.295
TK lost from soil water (t.ha^{-1})	-0.046	-0.299	-0.224	-0.272

*TK uptaken by leaf, wood and roots; $\Delta\text{TK}_{0-60\text{cm}}$, total variation of TK in soil from 0-60 cm (t.ha^{-1}); $\Delta\text{K}_{\text{av}_0-60\text{cm}}$ Total variation of available K in soil from 0-60 cm (t.ha^{-1})

Unlike TN, amounts of TK applied were of the same degree of magnitude than TK uptaken. As TK in soil decreased significantly during the experiment (Chapter 5, 3.10.2) under all covers, it reveals how insignificant the impact of implementing a WaterRenew system on TK dynamics in soil was.

Therefore the fate of TK applied would be explained by considering the amounts of TK uptaken by trees, variation in available K in soil and the amount of TK leached with soil water.

² Leaves +wood +roots: Roots biomass was accounted as 20 % of the above ground biomass. (Mc Cracken, personal communication)

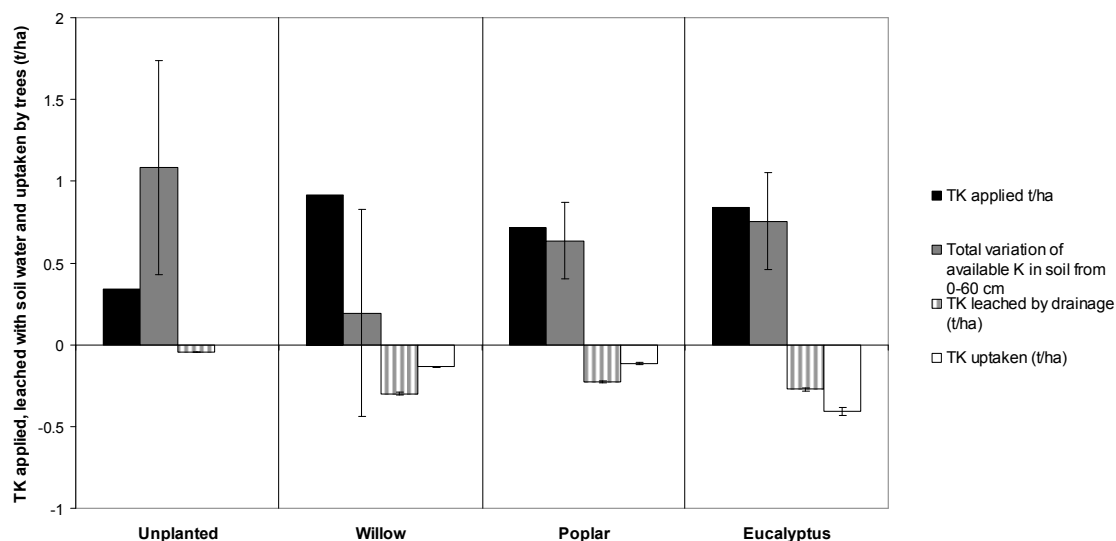


Figure 12 TK total balances in t.ha⁻¹ with TK applied, TK leached with soil water, TK uptake by trees after 3 years.

The pattern was the same for all covers: there was an increase in available K in soil. According to Chapter 5 (3.10.1), these increases were not related to irrigation as it happened also under non-irrigated plots.

Hence, applied K could be uptake by trees, leached in soil water or adsorbed onto soil inorganic matter or immobilised in soil organic matter (Sparks and Huang, 1985). When applied amounts were compared to the sum of uptake and leached TK amounts, there was always an excess; in other words, the totality of applied TK did not just end up in either plant or soil water but also in soil matter, organic or inorganic (Figure 12).

The amounts lost by drainage are of the same order of magnitude than the amount applied by irrigation for tree planted plots (drained TK amounts represent more than 30 % of the applied TK amount for planted plots but 14 % for unplanted plots). Therefore, the tree presence, especially the roots, may enhance K mineralisation, therefore leaching as K is solubilised into soil water solution from soil organic or inorganic matter (Sparks and Huang, 1985).

TK loss from soil was explained in Chapter 5 (3.10.2) as the result of soil weathering. However, TK loss also happened on non-irrigated plots. TK loss from soil will be assessed considering Na dynamics in soil. It is possible indeed that, K might have been replaced by Na added by irrigation during cation exchange processes (Rowell, 1994).

Na balance is calculated in the next section.

In terms of comparative efficiency for K removal or transformation, willow appeared again as the best performing for the same reason as for TP. Even though in net amount uptaken, the willow trees took up less than the eucalyptus trees (0.13 t.ha^{-1} against 0.41 t.ha^{-1}). Willow was the only cover to induce a net decrease in soil available K pool for comparable leached amount (0.299 t.ha^{-1} against 0.272 t.ha^{-1}).

However, the instalment of a WaterRenew did not have a significant effect on TK soil natural processes or balance.

4.4 NA BALANCE

First of all, tree Na uptake was not measured during this experiment.

According to Figure 13, on average more Na is leached with drainage than applied by irrigation. However, there is a build up of Na in soil and significantly (Chapter 5, 3.6). Moreover, Na budget does not balance: a decrease of Na in soil would be expected as Na is more leached than applied in average. But the total Na was not measured, and this increase might have resulted from non-ammonia nitrate extractable Na made more soluble as a result of irrigation, but this will remain a speculation as the experimental data are not available.

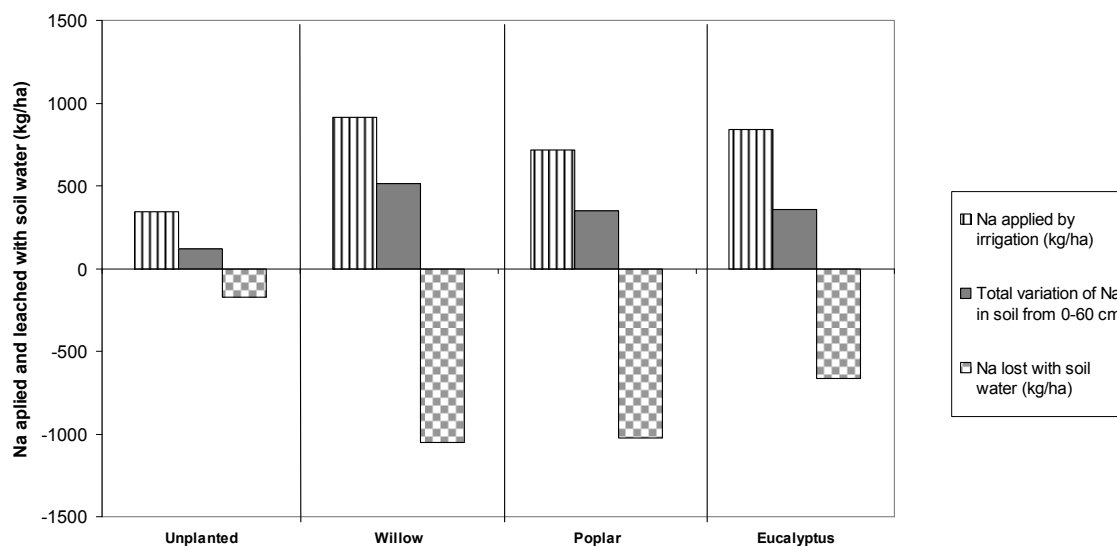


Figure 13 Na total balances in t.ha^{-1} with Na applied, Na variation in soil from the beginning of the trial to the end, for a layer of 60 cm, Na leached with soil water.

Nonetheless increases of Na are not of the same magnitude than TK loss; indeed TK losses were a hundred times greater than Na increase in soil. Hence, TK significant decrease could not be explained by Na replacement on the CEC.

Table 15 Comparison of variation of soil TK and Na during the period of experimentation. (SD for standard deviation) in t.ha⁻¹.

	<i>Unplanted</i>	<i>Willow</i>	<i>Poplar</i>	<i>Eucalyptus</i>
$\Delta\text{TK}_{0-60\text{cm}}$ (t.ha ⁻¹)	0.12	0.52	0.35	0.36
SD for $\Delta\text{TK}_{0-60\text{cm}}$ (t.ha ⁻¹)	0.38	0.44	0.18	0.53
$\Delta\text{TK}_{0-60\text{cm}}$ (t.ha ⁻¹)	-43.02	-30.54	-33.43	-43.26
SD $\Delta\text{TK}_{0-60\text{cm}}$ (t.ha ⁻¹)	-38.96	-49.34	-33.86	-42.81
$\Delta\text{TK}_{0-60\text{cm}} / \Delta\text{TK}_{0-60\text{cm}}$ (%)	0.3	1.7	1	0.8

*TK uptaken by leaf, wood and roots ; $\Delta\text{TK}_{0-60\text{cm}}$, total variation of TK in soil from 0-60 cm (t.ha⁻¹); $\Delta\text{K}_{\text{av}_0-60\text{cm}}$ Total variation of available K in soil from 0-60 cm (t.ha⁻¹)

5. CONCLUSION

The specific objectives of this chapter were:

- **Objective 1:** to estimate the water balance for Cranfield WaterRenew system.

This present chapter revealed that the irrigation settings were probably inducing drainage rather than only maintaining soil moisture to field capacity. These results are based on data calculation in which water balance was equilibrated using DIVINER data (soil moisture data every 10 cm on a profile of 1.7 m depth) to assess soil water storage variations. Drainage was also assessed using two other approaches, rainfall and variation in daily soil moisture data at 10 cm. As DIVINER data resulted in the highest amount of drainage, they were used to estimate nutrients leaching amounts as they would correspond to the worst case scenario. Hence, the willow plots were the ones, draining the most according to calculations based on DIVINER with 43 % of the total amount of water received either by rainfall or irrigation drained, compared to 41 % for eucalyptus, 38 % for poplar and 13 % for unplanted plots.

- **Objective 2:** to calculate the nutrient balances to assess nutrients fate in the system and estimate its efficiency or performance.

The fate of the different nutrients was then assessed:

- For total nitrogen, TN, the amounts of N leached were low even during the first year, dissimilar to the warnings from the literature (Aronsson and Bergstrom, 2001; Dimitriou and Aronsson, 2004; DEFRA, 2002.) and included under the unplanted plots. This showed the relative importance of soil capacity to immobilise N into soil organic matter. In terms of trees, as eucalyptus produced the greatest amount of biomass, eucalyptus were the best performing by uptaking 62 % of TN applied by irrigation. However, the total amounts of TN applied during the experiment ($\approx 500 \text{ kg-N.ha}^{-1}.\text{year}^{-1}$) remained negligible compared to soil TN pool (2 to 6 %). The proportion of N leached remained low as well, ranging from 5 % for unplanted plots to 13 % for planted plots.
- For total phosphorus, TP, there was no detectable phosphate or TP coming out of the WaterRenew field trial settled in Cranfield University. Therefore, again, soil relative importance in P fate was highlighted as there was no P detectable even in soil water coming from unplanted plots. For the trees, willow appeared to be the best performing. Even though considering the net amount, the willow

trees took up less than the eucalyptus trees (36 kg.ha^{-1} against 59 kg.ha^{-1}); willow was the only cover to induce a net decrease in soil Olsen-P pool. In effect, the less Olsen-P in soil, the lower the risk of P leaching (Heckrath et al., 1995). Therefore, willow trees or roots appeared to have an effect on soil organic matter by enhancing P immobilisation into organic matter. But the amounts of P applied were closer to the Olsen-P amount in soil. P applied corresponded to 30-60 % of Olsen-P. However, the Olsen-P under the different trees increased only under poplars and Olsen-P pools decreased under irrigated willow and eucalyptus. Olsen-P evolutions could not be linked to P application. This might be because Olsen-P corresponds only to a maximum of 15 % of TP in soil, and they remained low compared to soil TP pool.

- For total potassium, TK, willow appeared again as the best performing for the same reason as for TP. Even though on considering net amount, willow trees took up less than eucalyptus trees (0.13 t.ha^{-1} against 0.41 t.ha^{-1}), and willow was the only cover to induce a net decrease in soil available K pool for comparable leached amount (0.299 t.ha^{-1} against 0.272 t.ha^{-1}). Therefore, this net decrease represents a greater possibility for K application. However, the instalment of a WaterRenew did not have a significant effect on TK soil natural processes or balance. As it was reported for N and P, the amounts of K applied corresponded to less than 30 % of available K in soil, however, as available K in soil represents less than 10 % of soil TK pool, the amounts applied remained low for the system. The proportions of applied K leaching out of the system were not negligible; they ranged from 14 % for unplanted plots to 32 % for planted plots.
- The amounts of Na applied by irrigation corresponded to over 400 % of extractable Na present in soil. The WaterRenew system was not able to retain Na significantly and irrigation increased Na concentrations in soil water and in soil significantly. The amounts leached by drainage were also significant.

Thus, apart from Na, a WaterRenew system can be considered as efficient to remove nutrients from secondary treated effluent by irrigating SRC. However, a WaterRenew system cannot be recommended in the vicinity of an aquifer sensitive to salinity as there is a clear risk of salinisation.

Table 16 summarised the fate of nutrients applied on the field trial.

Table 16 Summary table of the fate of nutrients applied on the WaterRenew system installed in Cranfield University sewage treatment works (trees: willow, poplar and eucalyptus).

	<i>Accounted for (in % of applied amounts)</i>		<i>Unaccounted for (in % of applied amounts)</i>
	Tree uptake	Lost by drainage	?
N	22-62 %	12-13 % (5 % for unplanted)	25-66 % (95 % for unplanted)
P	18-45 %	0 % (0 % for unplanted)	55-82 % (100 % for unplanted)
K	15-49 %	31-33 % (14 % for unplanted)	19-53 % (86 % for unplanted)

On planted plots, tree uptakes may have contributed to retain the nutrients applied into the WaterRenew system. The proportions of nutrients lost by drainage were less important (especially for N and P) and prevented pollution of the groundwater. Therefore, the WaterRenew system protected and maintained groundwater quality. But as revealed in Table 16, the major proportion of N and P applied (>50 %) were unaccounted for and might be fixed or incorporated to soil organic and inorganic nutrients pools. N may be immobilised into soil organic matter or volatilised and P may have been mainly adsorbed by soil P sorption capacity. Yet because of the large sizes of soil nutrients pool and the associated errors in measurements, it was not possible to validate these nutrients' balances.

6. REFERENCES

- Allen, R. G. (1998.), *Crop evapotranspiration : guidelines for computing crop water requirements*, Food and Agriculture Organization of the United Nations, Rome.
- Aronsson, P. G. and Bergstrom, L. F. (2001), "Nitrate leaching from lysimeter-grown short-rotation willow coppice in relation to N-application, irrigation and soil type", *Biomass and Bioenergy*, vol. 21, no. 3, pp. 155-164.
- Avery, B. W., Bascomb, C. L., Soil Survey of England and Wales. and Hill, M. N. (1974.), *Soil survey laboratory methods*, Rothamsted Experimental Station, Lawes Agricultural Trust, Harpenden.
- Conrad, R., Seiler, W. and Bunse, G. (1983), "Factors influencing the loss of fertilizer nitrogen into the atmosphere as N₂O.", *J. Geophys. Res.*, vol. 88, pp. 6709-6718.
- DEFRA (2002.), *Growing short rotation coppice : best practice guidelines for applicants to DEFRA's energy crops scheme*. DEFRA, London.
- Dimitriou, I. and Aronsson, P. (2004), "Nitrogen leaching from short-rotation willow coppice after intensive irrigation with wastewater", *Biomass and Bioenergy*, vol. 26, no. 5, pp. 433-441.
- Heckrath, G., Brookes, P. C., Poulton, P. R. and Goulding, K. W. T. (1995), "Phosphorus Leaching from Soils Containing Different Phosphorus Concentrations in the Broadbalk Experiment", *Journal of Environmental Quality*, vol. 24, no. 5, pp. 904-910.
- Hellebrand, H. J., Scholz, V. and Kern, J. (2008), "Fertiliser induced nitrous oxide emissions during energy crop cultivation on loamy sand soils", *Atmospheric Environment*, vol. 42, no. 36, pp. 8403-8411.
- Hillel, D. (1980), *Applications of Soil Physics*. Academic Press.
- Houghton, J. T. and Intergovernmental Panel on, C. C. (1997), *Greenhouse gas inventory reporting instructions*, [Rev. ed.] ed, IPCC, Bracknell.
- Jørgensen, S. E. and Endorichio, G. (2001), "Fundamentals of ecological modelling. 3rd edition", vol. 21, pp. 1-530.
- Jorgensen, U. and Schelde, K. (2001), "Energy crop water use and nutrient use efficiency", *IEA Bioenergy Task 17, Short Rotation Crops*, .
- Liu, C., Yeh, H. and Sheu, B. (2006), "N isotopes and N cycle in a 35-year-old plantation of the Guandaushi subtropical forest ecosystem, central Taiwan", *Forest Ecology and Management*, vol. 235, no. 1-3, pp. 84-87.
- MAFF, (2000), *Fertiliser recommendations for agricultural and horticultural crops (RB209)*, Seventh edition ed., the stationary office, London, UK.
- MAFF (1986.), *The analysis of agricultural materials : a manual of the analytical methods used by the Agricultural Development and Advisory Service*, 3rd ed, HMSO, London.

- Pierzynski, G. M. (2000), "*Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters*", *Southern Cooperative Series Bulletin*, vol. 396, pp. 102.
- Rowell, D. L. (1994), *Soil science : methods and applications*, Longman Scientific & Technical, Harlow.
- Sharpley, A. N., Curtin, D. and Syers, J. K. (1988), "Changes in Water-extractability of Soil Inorganic Phosphate Induced by Sodium Saturation", *Soil Science Society of America Journal*, vol. 52, no. 3, pp. 637-640.
- Smith, C. J., Snow, V. O., Polglase, P. J. and Probert, M. E. (1999), "Nitrogen dynamics in a eucalypt plantation irrigated with sewage effluent or bore water", *Australian Journal of Soil Research*, vol. 37, no. 3, pp. 527-544.
- Sommers, L. E. and Nelson, D. W. (1972), "Determination of Total Phosphorus in Soils: A Rapid Perchloric Acid Digestion Procedure", *Soil Sci Soc Am J*, vol. 36, no. 6, pp. 902-904.
- Sparks, D. L. and Huang, P. M. (1985), "Physical chemistry of soil potassium. In R.D. Munson (ed.) Potassium in Agriculture.", *Soil Science Society of America*, , pp. 201-276.
- Ward, A. D., Trimble, S. W. and Wolman, M. G. (2004), "Environmental Hydrology", , pp. 475.

CHAPTER 8: PHOSPHORUS LEACHING AS AFFECTED BY WASTEWATER APPLICATION AND SOIL MOISTURE LEVELS

1. INTRODUCTION

Phosphorus (P) issues are treated widely in the literature as P is a very important factor in biomass production. This is for two reasons, firstly because it is usually the limiting factor to biomass production in freshwater and secondly because a very little concentration of it has a significant effect on biomass production (Gibson, 1997). That is how P fate is systematically considered as it can be, with incorrect management, applied as a fertiliser on field to a contaminant in surface waters, causing algae blooms or eutrophication; with devastating disequilibrium in oxygen and nutrient balance (Gibson, 1997).

For this reason, during a field trial at Cranfield University, Bedfordshire, UK, where a WaterRenew system (a wastewater polishing system using renewable energy crops), P issues were considered carefully over the 3 years of experimentation, from July 2006 to February 2008. In this trial, the secondary treated effluent was irrigated on willow, poplar and eucalyptus planted plots and unplanted plots. Despite an average loading of 125 kg-P.ha^{-1} over 2 years, there was no P detected ($<0.01 \text{ mg-P.L}^{-1}$, Burkhardt autoanalyser detection sensibility) in soil water samples monitored fortnightly at 30 and 60 cm depth. As the field was lying on a calcareous clayey soil (Hanslope, 411d, (NSRI, 2008)), an Olsen-P of 22 mg-P.kg^{-1} of soil ($< 60 \text{ mg-P.kg}^{-1}$ of soil, (Heckrath et al., 1995)) was measured initially, a relatively high P sorption capacity was expected (Djodjic et al., 2004) but still some P was expected to appear in soil solution, at least under unplanted irrigated plots. Hence, one objective of this experiment was to understand P leaching behaviour from Cranfield soil.

In general, despite extensive experimentations on P and because of their high complexity, the release of P, and in particular its leaching processes, are very difficult to forecast. It was not possible to identify an adequate unique indicator to forecast or predict P leaching from P application to soil into soil water and consequently groundwater (Djodjic et al., 2004, McGechan, 2002; McGechan and Lewis, 2002; Mamo et al., 2005).

To understand how to apprehend P leaching processes from its application in effluent or in solution, to its transfer into soil solution, it is important to acknowledge the different forms of P in soil and soil solution and moreover, how these different forms do equilibrate. Pierzynski (2000) described the different forms of P in soil as, fractionation of inorganic-P from more mobile to more sequestered in soil matrix:

- soluble and loosely bound P, this includes plant available P or Olsen-P
- P bound on soil matrix aluminium ion, Al-P
- P bound on soil matrix iron ion for non-calcareous soil, Fe-P
- Reductant soluble P for calcareous soil
- P bound on soil matrix calcium ion for both type of soils, Ca-P.

Then, to leach, P needs to be in solution. Equilibrium of P between sediments, soil particles, matrix and soluble P is driven chemically by 2 mechanisms depending on soil types; the first mechanism is due to redox potential, because changes in redox state of Fe would influence Fe-P availability. Or the second mechanism results from changes in pH, as these induce changes of forms of Ca and Ca-P availability for calcareous sediments (Gibson, 1997). Hence, different definitions of P sorption capacity of a soil were given depending on the amount/availability of P “boundable” Al/Fe/Ca sites in a soil (Pierzynski, 2000). The different definitions will be presented in the first part of this chapter.

A way to control both redox and pH conditions in soil is to control its moisture content. Zarate-Valdez et al., (2006) quantified the relationship between soil moisture, pH and redox potential: when soil moisture increases, pH increases and redox decreases.

For this reason, in the experiment described in this paper both the influence of P concentration in the solution applied to soil, and the way it was administrated, i.e. on varying soil moisture content, therefore pH and redox potential, were studied. This experiment is part of a wider project seeking to move forward the understanding of soil based wastewater treatment, coupled with short rotation coppice management, its feasibility and sustainability. Hence, to answer the feasibility and sustainability aspect of a WaterRenew system, it was primordial to understand how applied P, as soluble P, enters any of the P –pools in soil, and whether it accumulates or not. In particular, the way P is applied as soluble P becomes Olsen-P or total phosphorus in soil was studied in the particular case of Cranfield University field trial. Another motivation for quantifying these processes lies in the attempt to model P accumulation in soil. This

model will be used to forecast sustainability of a WaterRenew system within a spreadsheet model, WR_MODEL, developed to design and assist decision making for any implementation of a WaterRenew system on a specific site.

The aim of this chapter, by setting a disturbed column experiment, is to understand P leaching dynamics and the specific objectives of this chapter are to:

- **Objective 1:** identify, quantify and understand the fate of P applied in solution on a clayey soil (proportion immobilised, proportion leaching).
- **Objective 2:** identify the effect of soil moisture on P leaching patterns.
- **Objective 3:** identify the effect of the concentrations at which P is applied on P leaching patterns.
- **Objective 4:** develop a relationship between P applied and P leached or a relationship between P applied and P immobilised in soil to help forecasting P leaching.

This chapter will present some principles on the forecasting of P leaching first, then will describe this experiment of P leaching affected by different concentration of P and soil moisture states, and finally the way P is built up in a soil profile (TP and Olsen-P).

2. MAXIMUM P SORPTION CAPACITY: DEFINITION AND DETERMINATION METHOD

The determination of a maximum P applicable before observing P leaching is important. The following section presents different definitions and approaches to assess this maximum amount of P applicable.

2.1.1 Olsen-P threshold

Olsen-P corresponds to extractable phosphate in soil, extracted with sodium bicarbonate. It can be used to determine an availability index for plants (Rowell, 1994) (MAFF 2000).

The initial Olsen-P was also of interest as Heckrath (Heckrath et al., 1995) determined a threshold of 60 mg-P.kg^{-1} of soil, above which soil is likely to start leaching P, hence this could be seen to define the maximum P sorption capacity. Moreover, RB 209 (MAFF 2000) guidelines and recommendations for fertilisers' applications for optimum economic return also uses Olsen-P to determine soil P index, consequently determining Cranfield soil Olsen-P appeared relevant.

However, Hooda et al. (Hooda et al., 2000) concluded with their studies on the relationship between P soil indices and potential P release to water that, for P release to water, there was “no or poor relationship with either soil P content or P sorption capacity (i.e. capacity factors), the most important property was the extent to which the soils were saturated with P.” In particular, the degree of phosphorus saturation approaches.

2.1.2 Freundlich equation from phosphorus sorption isotherm

Phosphorus sorption isotherm measurements consist of measuring a soil's capacity to adsorb P by mixing it with solutions of different P concentrations for 24 hours at room temperature. With the previous isotherms data, it is possible to plot the relationship between P sorbed by soil (mg.kg^{-1} of soil) and equilibrium P concentration in solution (mg-P.L^{-1}).

The Freundlich equation is one of the models representing this relationship and can be linearised by a neperien logarithm transformation of the data (Pierzynski, 2000) (Equation 1)

$$S = K * C^{\frac{1}{n}}$$

$$\ln(S) = \ln(K) + \frac{1}{n} * \ln(C) \quad \text{Equation 1}$$

Where (Pierzynski, 2000):

- S is the total amount of P retained, mg.kg^{-1} .
- C is concentration of P after 24 h equilibration, mg.L^{-1}
- K is the adsorption constant, expressed as mg-P.kg^{-1} ,
- $1/n$ is a constant expressed as L.kg^{-1} .

Hence, plotting $\ln(S)$ against $\ln(C)$, a linear relationship will be obtained with $1/n$ as slope and $\ln(K)$ as intercept.

3. MATERIAL AND METHODS

The experiment described in this chapter was conducted with Cranfield soil. Soil samples were air dried and <2 mm sieved prior to analysis. The columns building were initially sampled from:

- For initial Olsen-P measurement and isotherms' construction: soil was sampled on Cranfield University field site at a place where neither treatment nor planting occurred (on one of the spare space), at 10, 30 and 50 cm depth, with a 5 cm auger, in February 2006.
- For columns building, soil was sampled at the same place as the one used for the other analysis but in November 2007, with a spade. This soil did not receive any treatment, neither irrigation nor planting.

3.1 INITIAL SOIL PHOSPHORUS CHARACTERISATION

Soil samples were taken while the soil was collected to build the columns and analysed for initial Olsen-P. Nine replicates of soil samples, taken in February 2006 at three depths (10, 30 and 50 cm), were used to determine the Sorption isotherm. February 2006 was prior to any treatment. All the measurements were averaged to obtain a 0-50 cm layer unique value and the standard deviation is reported.

3.1.1 Olsen-P determination

The methodology followed is described in Rowell (1994) (Rowell, 1994) and developed by Olsen (Olsen et al., 1954.).

Olsen-P is defined as P extracted in sodium bicarbonate: 5±0.05 g of soil (air dried and <2 mm sieved) are extracted with 100 mL of sodium bicarbonate solution (0.5 M NaHCO₃ at pH= 8.5) and shaken end-up for 30 minutes at room temperature. The extract is then filtered and the P concentration is determined in the filtrate by measuring phospho-molybdate by spectrophotometry.

3.1.2 Phosphorus sorption Isotherm determination

Phosphorus sorption isotherm measurements consist of measuring a soil's capacity to adsorb P by mixing it with solutions of different P concentrations for 24 hours at room temperature (Rowell, 1994)(Torrent and Delgado, 2001). For this purpose, 2.5 g (± 0.01 g) of < 2 mm air dry soil were shaken in bottles for 24 hours with 25 mL of the

standard phosphorus solutions, the P concentrations were 0, 10, 20, 40, 70, 100 mg.L⁻¹. Standard solutions were made by solubilising appropriate amounts of KH₂PO₄ in 2.5 mL of 0.4 M CaCl₂ solution and made up to 100 mL with distilled water. Then, solutions are filtered through Whatman No. 42 papers, rejecting the first few ml and the concentration of P in the filtrate determination with molybdate blue method described by Murphy and Riley (Murphy and Riley, 1962).

3.2 SOIL COLUMNS

This experiment was based on a previous experiment conducted in Park Rapids, MN, USA, (Mamo et al., 2005), where the objective was to “evaluate the effects of soil P levels and temperature on P leaching in soil columns”. The soil used was sandy loam with two initial soil-P contents.

In the experiment conducted by Mamo et al. (2005) unstructured, disturbed soil columns were built. The same procedure was used to build the columns in this experiment. It was expected that the physical properties of the columns due to packing, even with the same bulk density, air dried, sieved soil, would be different for the same volume and mass of soil in a structured column, especially the hydrological properties (Persson and Berndtsson, 1998). Hence, one of the disadvantages of using unstructured columns is that the results might not represent the reality of the field. However, one of the advantages of unstructured columns is that it is possible to approach a good homogeneity of the different replicates as columns are built up the same way. In the context of this experiment, there was a practical reason for choosing unstructured columns, as there was not enough undisturbed soil surface to be able to collect the appropriate number of structured soil columns.

3.2.1 Preparation of columns

Columns (polythene) of 10 cm diameter and 27 cm length were filled until 25 cm with air-dried, 2 mm sieved soil. The length of 27 cm is chosen to get the same ratio for diameter to length used by Mamo et al. (2005) (16 cm diameter for 40 cm length). A fine mesh screen with 220 g of coarse sand were placed at the bottom of every column and very fine sand (200 g) was layered at the surface of the columns to guarantee an even P application onto the column surface and to avoid preferential flows to develop.

Soil columns were filled with Cranfield clayey soil to have the same bulk density as in the field $\rho=1.22 \text{ g.cm}^{-3}$. Therefore, the 2.395 kg of soil used to fill each column were packed 5 cm by 5 cm and compressed to the right volume. Columns were let to settle for 2 days and were kept indoors for the duration of the experiment.

The columns were gradually saturated from the bottom with distilled water. Once saturated, they were flushed with 375 mL, from the top. This flush had two objectives, first to flush out any residual nutrients and second, to have a background reading of soil water P before starting the experiment.

3.2.2 Phosphorus leaching experiment: hypothesis and four treatments

Three replicates of columns were set up under four different treatments:

- i. Continuous application of low P concentration solution (4 mg-P.L^{-1} as phosphate) or typical secondary treated effluent P concentration (Mamo et al., 2005), at a rate of 1 mm.hour^{-1} .
- ii. Continuous application of high P concentration solution (40 mg-P.L^{-1} as phosphate) or typical primary treated effluent P concentration (Mamo et al., 2005), at a rate of 1 mm.hour^{-1} .
- iii. Intermittent application of high P concentration solution (40 mg-P.L^{-1} as phosphate) with exposure to heating lamp while not irrigated (to mimic succession of dry and hot conditions and wet conditions of summer resulting in cracks formation allowing possibly bypass flows. Those columns were not layered at their surface with the fine sand),
- iv. Intermittent application of low P concentration solution ($4 \text{ mg-P. mg-P.L}^{-1}$ as phosphate).

P feeding solutions were made by:

- For the high P solution, 40 mL of a 1 g.L^{-1} of solution of KH_2PO_4 was diluted and made up to 1 L of 40 mg-P.L^{-1} of feeding solution.
- For the low P solution, 4 mL of a 1 g.L^{-1} of solution of KH_2PO_4 was diluted and made up to 1 L of 4 mg-P.L^{-1} of feeding solution.

Then the following hypotheses were formulated:

- Treatments (i) and (ii)

As P is applied constantly at the head on initially saturated columns, water should be pushed through the columns at a constant rate. At some point, P applied should fill soil P sorption capacity then reach a value close to 100% Degree of Phosphate Saturation, DPS, and should start leaching from the columns. For this reason, P concentration in the feeding water should reflect the rate at which soil is becoming saturated with P, therefore, reflecting the speed at which P will start to leach from the columns.

Hence, it is expected to observe P leaching faster from columns fed with the high P feeding solution than from columns fed with the low P feeding solution.

- Treatment (iii)

During the summer, high radiation rates and temperatures dry the soil surface. With clayey soil, these conditions create cracks on the soil surface. These cracks become preferential flows for water to infiltrate. The apparition of bypass flow paths will result in P leaching out of the system before reaching soil P maximum capacity in the column. (Thomas et al., 1997)

- Treatment (i) in comparison with treatment (iv)

P sorption in saturated conditions is greater than in unsaturated conditions when applied at the same concentration on the feeding water as contact time will be greater.

3.2.3 Flow uniformity check with bromide spiking

Despite sand layered on column surfaces to distribute feeding solution evenly, preferential flow could still happen. Hence, to check and visualise solution flow within columns, P feeding solution was spiked with Br at a concentration of 50 mg-Br.L^{-1} . Br is inert and does not react with any component of the soil (Mamo et al., 2005).

An initial spiking took place from day 3 (02/02/08) to day 11 (10/02/08) of the experiment resulting in a total Br application of $54.6 \pm 2.9 \text{ mg-Br}$.

To monitor if there was no changes in the hydraulics within the columns, the second spike took place from day 69 (10/03/08) to day 70 (11/03/08) of experiment with a total Br application of $7.2 \pm 3.6 \text{ mg-Br}$. This second spike was shorter than the first one as we learnt from the first spike that a smaller amount of Br was enough to be detected.

3.2.4 Leachate and soil analysis

Leachate was sampled daily and phosphate and total phosphorus (TP) concentration determined by Burckhardt Automatic Ion Analysers. The model used is based on the principle of Segmented Flow Continuous Analysis technique introduced by Dr L. Skeggs in 1957 (Analyser guide book).

pH was also measured weekly in all leachate.

Bromide was measured in leachate as bromine using ICP-MS (Inductively Coupled Plasma Mass Spectrometry).

Prior to the experiment, TP (Aqua regia digestion), Olsen-P (Olsen et al., 1954.) and DPS, Degree of Phosphorus Saturation (Van der Zee and van Riemsdijk, 1988) were measured on soil samples used to build the columns.

For soil samples, 5 cm depth layers were air-dried, 2 mm sieved and homogenized for Olsen-P determination (Olsen et al., 1954.), and finely ground for TP analysis (Aqua regia digestion and colorimetry).



Picture 1 column setup with P solution feeding system. P solution is delivered over 12hours with a peristaltic pump through a dripping system. Leachate is collected daily at the bottom at the columns.



Picture 2 Side view of column's setup.

3.3 DATA ANALYSIS

Each treatment was replicated three times, allowing for consistent statistical analysis. For both leachate P concentrations and soil P (Olsen-P or aqua regia TP), three factors were used to attempt to explain their evolution. Thus, general linear models (GLM, Statistica 8.0) were fitted to those variables, leached P amount (mg) in leachate, Olsen-P and total phosphorus (TP) in soil. The factors taken in account were applied P concentration (two levels, High or 40 mg-P/L and Low or 4 mg-P.L⁻¹), application rate (two levels, continuous or intermittent), day of experiment (181 days) for leached P and depth from surface of the column for soil P (5 variants, 0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm, 20-25 cm). The factors of day of experiment and depth were nested with the principle factors applied P concentration and application rate (Equation 2).

Equation 2 General linear model

$$X = \alpha + \beta_{\text{Applied P concentration}} + \gamma_{\text{Application rate}} + \gamma\beta_{\text{Applied P*Rate}} +$$

$$\text{or } \delta_{\text{Day}}(\gamma\beta) + \varepsilon \quad (\text{for leached P})$$

$$\text{or } \tau_{\text{Depth}}(\gamma\beta) + \varepsilon \quad (\text{for soil P})$$

- X: measurable variable
- α : constant

- $\beta_{\text{Applied P concentration}}$: Factor Applied P concentration (two levels)
- $\gamma_{\text{Application rate}}$: Factor application rate (two levels)
- $\gamma\beta_{\text{Applied P*Rate}}$: Interaction of Applied P concentration and application rate factors contribution
- $\delta_{\text{Day}}(\gamma\beta)$: Factor day of experiment or date (31/01/08 corresponding day 1) only for leached P, one level under the fixed factors Applied P concentration and application rate, for this reason, it is nested.
- $\tau_{\text{Depth}}(\gamma\beta)$: Factor Depth contribution (5 levels) only for soil P, one level under the fixed factors Applied P concentration and application rate, for this reason, it is nested.
- ε : residuals

A parametric Analysis of Variance (ANOVA) was conducted to determine significant differences in comparison of variances allocated to the previous factors.

An LSD test at $P < 5\%$ evaluated the effect of significant factors.

Another objective of the WaterRenew project within which this experiment was set up was the development of a model as a tool to assist design, feasibility and sustainability of a WaterRenew system. And one of the limits to sustainability of a WaterRenew system is the accumulation of P; build up of P or the extent to which soil is saturated with P linking directly to the potential of P release in water (Hooda et al., 2000). Hence, to develop this model, there was a need to know how the soil P saturation is changing when this soil is irrigated with effluent. The results of this column experiment and in particular the relationship that develops between the amounts of P added in solution with the subsequent changes in Olsen-P or TP in soil will be used in the WR_MODEL spreadsheet model (WR_MODEL is described in Chapter 9).

4. RESULTS AND DISCUSSION

4.1 INITIAL SOIL PHOSPHORUS CHARACTERISATION

4.1.1 Initial Olsen-P

Olsen-P concentration in soil used to build the columns was $22 \pm 5 \text{ mg-P.kg}^{-1}$ of soil. According to Heckrath (Heckrath et al., 1995), P should start leaching in drainage water when Olsen-P in soil reaches 60 mg-P.kg^{-1} . Hence, as columns were made up with 2.395 kg of soil with an original Olsen-P of $22 \pm 5 \text{ mg-P.kg}^{-1}$ of soil, a minimum of $91 \pm 11 \text{ mg-P}$ could be added to each column before observing any P leaching, minimum as this value assumed all P applied would become Olsen-P.

This Olsen-P content relates to an Olsen-P of $1.10 \pm 0.25 \text{ mg-P.L}^{-1}$ and a P index of 0 according to RB209 (MAFF 2000).

4.1.2 Phosphorus sorption Isotherm and Freundlich equation

Freundlich model parameters were calculated from linear regression of logarithm data. Then, for the set of equilibrium P concentrations, C, the corresponding P sorption amounts, S, were calculated.

The best fit of Freundlich modelled data with observed data were assessed by linear regression and observation of slope ($a=0.91$) and determination coefficient ($R^2=0.98$) and considered acceptable (Figure 1). Freundlich model fitted to Cranfield soil data was:

$$S = 138 * C^{0.26}$$

with S : sorbed P (mg-P.kg^{-1} of soil)

C : P equilibrium concentration in solution (mg-P.L^{-1})

The Freundlich parameter doesn't give directly the maximum P sorption capacity; however, it tends to a plateau value. Hence, S_{\max} was assessed graphically to $420 \pm 60 \text{ mg-P.kg}^{-1}$ of soil.

The Freundlich model constants fitted on Cranfield chalky clayey soil are in accordance with the values reported in the literature. A study on calcareous clay P sorption characteristics (Zou et al., 1992; Zhou and Li, 2001) reported for a soil with a clay content of 60.3 %, a K_f of 159 mL.g^{-1} and a $1/n$ of 0.43. However, for S_{\max} , for this soil the value reported was $2897 \text{ mg-P.kg}^{-1}$ of soil or 6.9 times more than Freundlich graphically adjusted for Cranfield soil.

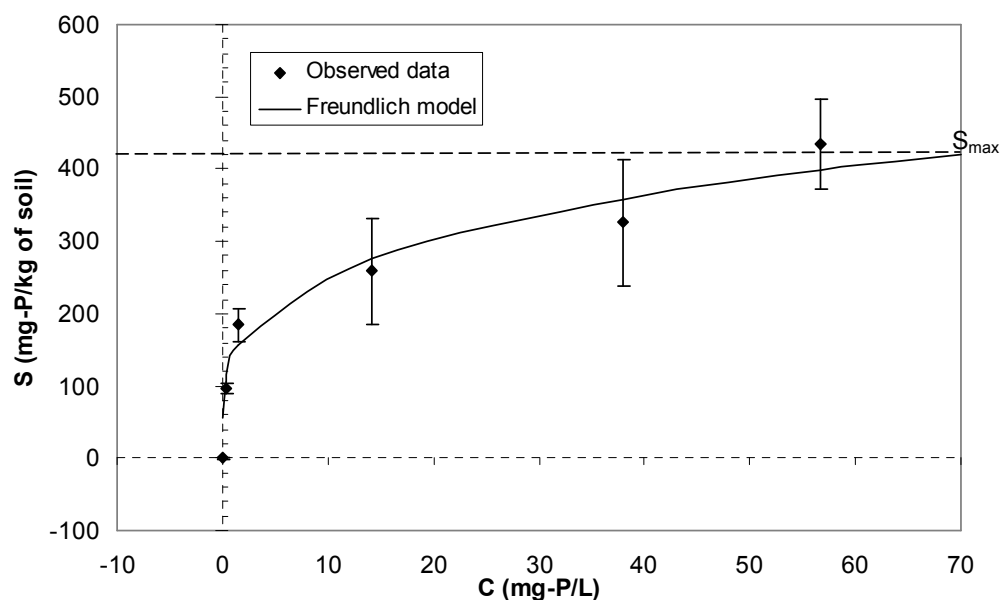


Figure 1 Curvilinear line is fitted Freundlich isotherm through all data points. With the equation $S=138 \cdot C^{0.26}$ ($R^2=0.98$ and slope of 0.91 for linear regression between observed data and modelled data). (---) S_{\max} graphically adjusted and was assessed at 420 ± 60 mg-P.kg⁻¹ of soil.

As S_{\max} were determined with two methods, the amounts of P addable before P start leaching are reported in Table 1.

Table 1 Comparison of maximum P sorption capacities calculated or evaluated from different method, Olsen-P and Freundlich model.

	Heckrath (<i>Heckrath et al., 1995</i>)Olsen-P	Freundlich model derived
Threshold considered (mg-P.kg ⁻¹ of soil)	Maximum Olsen-P in soil: 60 mg-P.kg ⁻¹ of soil	$S_{\max} = 420 \pm 60$ mg-P.kg ⁻¹ of soil
Corresponding amount of P addable per column (mg)	Minimum of 91	1006

$S_{\max_Freundlich}$ is almost 10 times greater than $S_{\max_Heckrath}$. However, for Heckrath, 91 mg is a minimum value as it is the amount to reach 60 mg-P.kg⁻¹ of soil if all P applied becomes Olsen-P. However, the relationship between the amount of P-applied and the corresponding subsequent Olsen-P increase in soil is not known in general and for Cranfield chalky clayey soil in particular.

In reality, especially for clayey soil, S_{\max} is very high, infiltration rate is average and normal effluent P contents are in comparison very low. Hence, it is unlikely to reach S_{\max} very quickly. Hence this experiment was set to assess the behaviour of soil when it is reaching or has reached S_{\max} .

The curve: P-leached (or adsorbed) = $f(P \text{ applied } (g-P/dt)*t)$ will be fitted (with t for time).

4.2 PHOSPHORUS LEACHING BEHAVIOUR

4.2.1 Bromide spiking results

Before analysis of the leaching patterns, Br spiking results will be presented. They can reveal how the feeding solution was travelling inside the columns; in particular if there were any preferential flows. As they would ensure if the feeding solution was delivered homogeneously and travelling the column without a preferential path (Mamo et al., 2005).

2 subsequent spikes were injected and Br leaching monitored.

Test 1 (Figure 2) took place from day 3 to day 11. The high P intermittent columns were not in place yet. For the 3 treatments, leaching patterns were different from preferential flow ones. Indeed, Br in leachate didn't appear at the same rate as it was applied but with a delay for the 3 treatments and the amount of Br leached per day was different from the amounts applied. High P, saturated columns (Figure 2, a) Br leaching pattern looked homogeneous. It took 4 days after application for Br to appear in leachate. Then another 4 days for Br concentrations to reach a "cruising" rate of 17 mg.2 day^{-1} in average and disappear again (concentrations lower than the detection limit of ICP). However, only 152 mg of the 299 mg applied were leached out. For low P saturated columns (Figure 2, b), the leaching pattern looked the same as for high P saturated columns even though Br apparition in leachate was at a faster rate and the "cruising rate" was of 14 mg.2 day^{-1} on average. As for high P saturated columns, less than a third of Br applied was leached (111 mg leached but 345 mg applied). For low P intermittent columns (Figure 2, c), the same kind of pattern was observed, however, as feeding solution was applied intermittently, less leaching occurred and only $1/8^{\text{th}}$ leached (44 mg out of 345 mg applied). During that first test, the whole amount of Br applied didn't leach for any of the columns. As Br cannot be adsorbed (Mamo et al., 2005), it means that even if there was solution ponding on surface of the saturated columns, the whole profile was not saturated. There were zones of the column where soil moisture remained under field capacity. Therefore there was no drainage in those zones and Br remained there, without being leached as no solution to transport it.

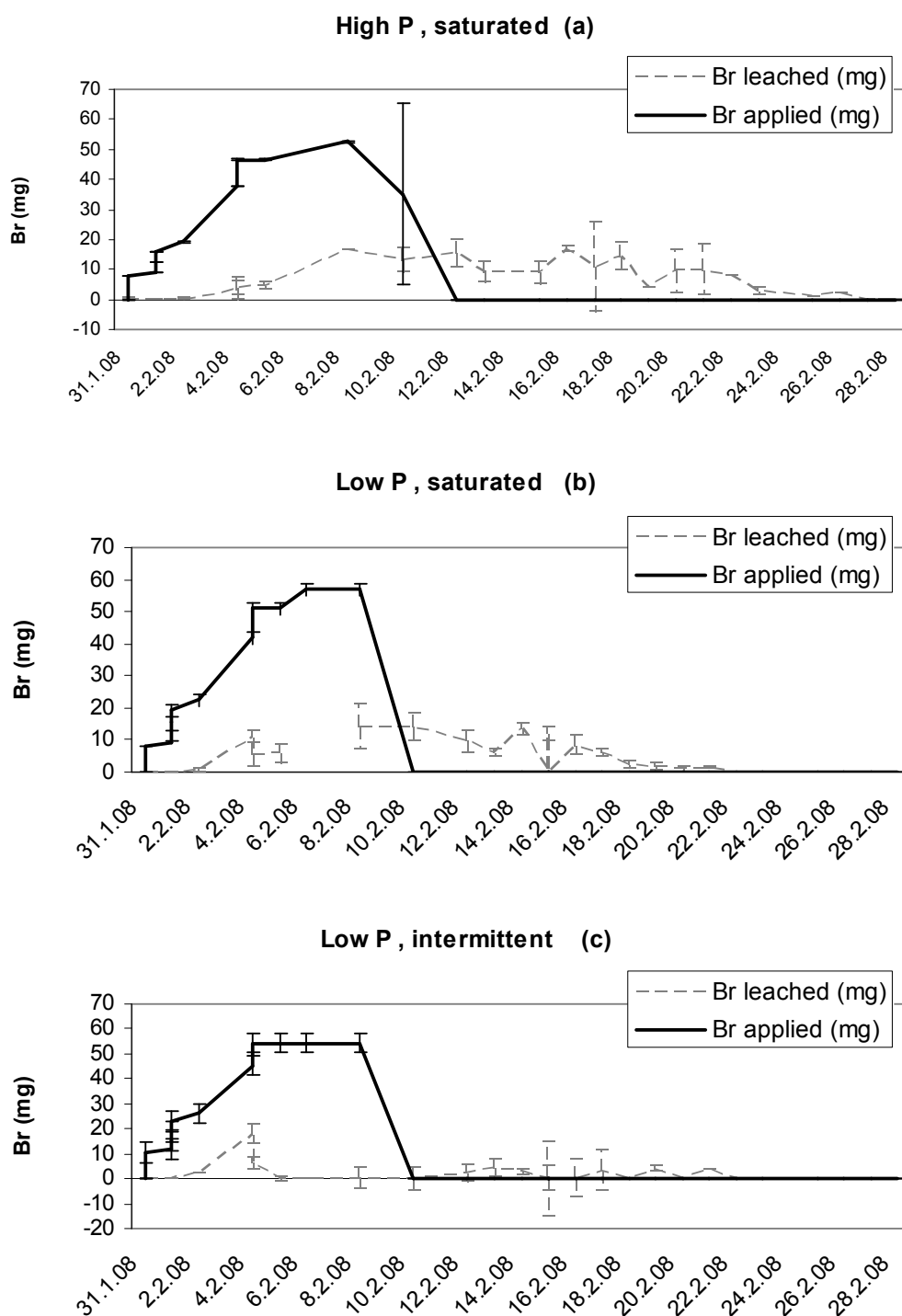


Figure 2 Evolution of bromide leaching test on soil columns, High P and Low P applied to keep a constant saturation and Low P applied intermittently. The mass of Br leached is reported with \pm standard deviation calculated from the 3 replicated columns.

The second test was performed to check if no preferential developed after another month of experimentation. Br was applied only for 2 days, day 37 and 38.

For saturated columns, leaching patterns were similar to the one observed during test 1; (Figure 3, a, b) i.e. a delay between Br application and Br apparition in leachate, a progressive increase in leachate until a “cruise” rate around 5 mg.day^{-1} . Br applied during test 1 was leached as well as during test 2, for high P columns, a total of 20 mg of Br was leached but 6 mg was applied and for low P columns, 15 mg leached but 4.5 mg applied. There is still Br applied missing. This phenomenon revealed that still, even with solution pounding on column surface, there are still air pockets in the columns where Br is trapped as there is no solution to transport it. For intermittent columns, leaching patterns revealed clear preferential flows (Figure 3, c, d) as there was no delay between the peak in Br applied and Br leached. Then, the patterns observed were comparable to the ones for saturated columns. As for test 1, all Br applied was not leached out (high P, 13 mg applied and 9 mg leached, low P, 5 mg applied and 3 mg leached). For saturated columns, as they were placed to dry under a lamp while not receiving P, cracks were formed on the surface on purpose in order to induce preferential flows.

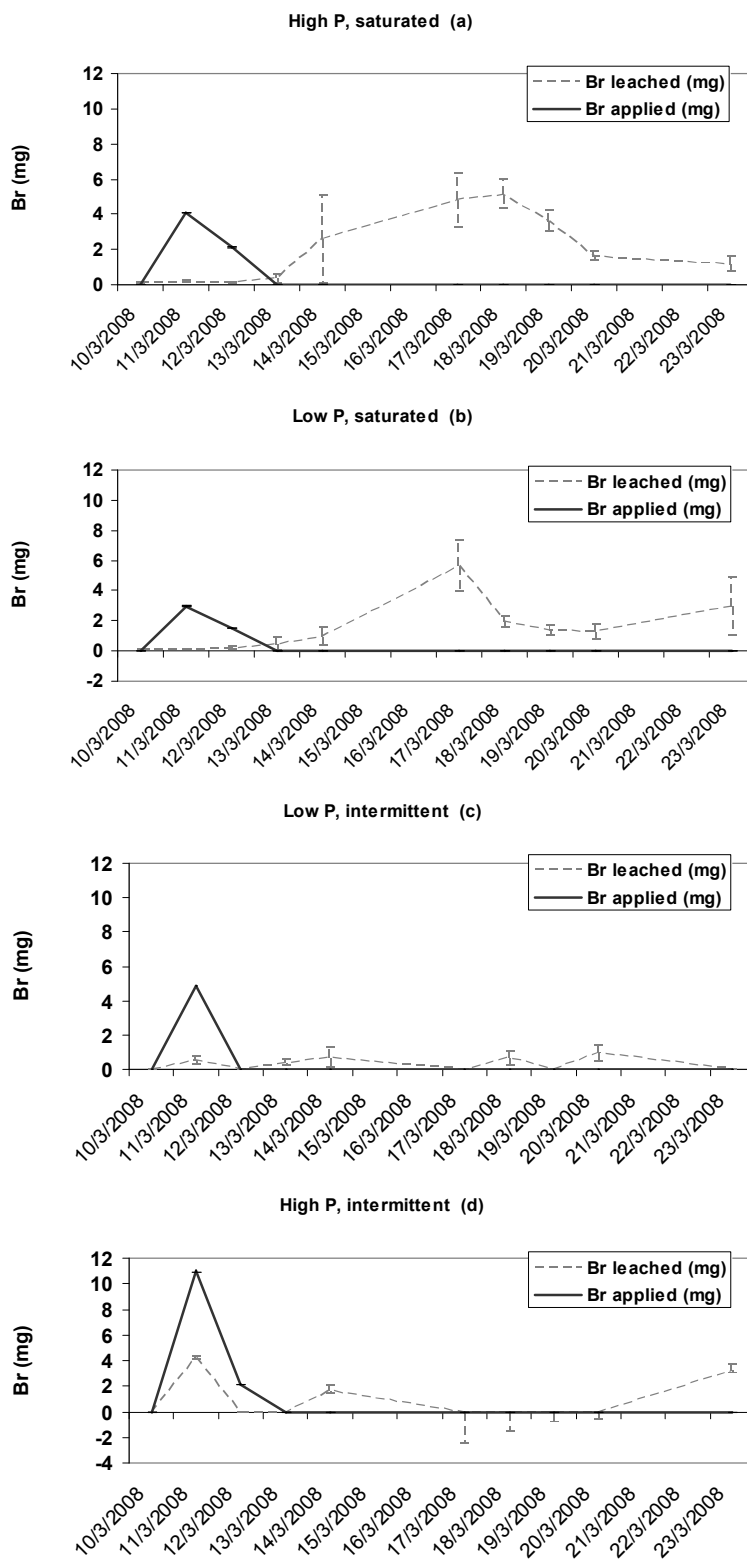


Figure 3 Evolution of bromide leaching test on soil columns, High P and Low P applied to keep a constant saturation and intermittently. The mass of Br leached is reported with \pm standard deviation calculated from the 3 replicated columns.

4.2.2 pH measurements in leachate

pH were measured regularly in leachate and feeding solutions in order to monitor any eventual sudden changes.

ANOVA was performed on pH data following the same general linear model as for log(TP). All factors considered had a significant effect on pH. High P solutions ($\text{pH} = 5.16 \pm 0.12$) were more acidic than low P ones ($\text{pH} = 6.08 \pm 0.5$). Hence, it was expected that pH from leachate from high P fed columns would be more acidic than pH from leachate from low P fed columns (Table 2).

Table 2 ANOVA table for pH from columns fed with high and low P solution continuously or intermittently (bold when significant $p < 0.05$)

	Degree of Freedom	pH - F	pH - p
Intercept	1	135540.7	0.00
Date(P concentration*Application rate)	27	4.4	0.00
P concentration	1	8.2	0.01
Application rate	1	43.0	0.00
P concentration*Application rate	1	31.9	0.00
Error	61		
Total	91		

First, all pH measured from leachate were greater than 7. This shows soil buffering capacity as both P solutions added were acidic (Rowell, 1994).

For intermittently fed columns, concentration of P in the feeding solution didn't decrease pH significantly. For saturated columns, the high P solution significantly decreased the leachate pH.

For low P columns, on average pH in leachate from intermittently fed columns were more acidic than pH from saturated columns. This should be explained by the fact the higher moisture content of the saturated columns increased pH as well (Zarate-Valdez et al., 2006). (Figure 4)

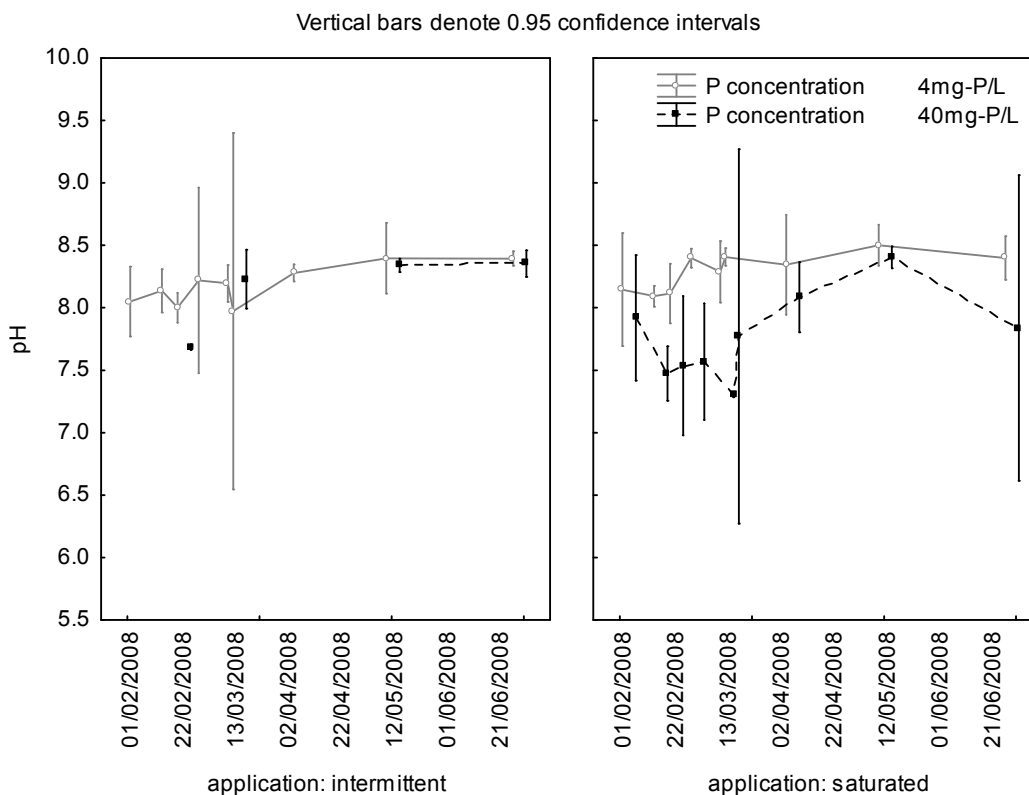


Figure 4 Evolution of pH measured from columns fed with high and low P solution intermittently or continuously to maintain saturation.

4.2.3 Phosphorus leaching pattern

The evolution of phosphate, PO_4 and total phosphorus, TP, concentrations in leachate are presented in Figure 5. P was applied as phosphate onto the columns and TP was also measured in leachate in case the phosphate changed form. However, phosphate and TP are correlated as phosphate represented 91% of TP ($R^2=0.99$). For this reason, essentially TP leached data will be presented.

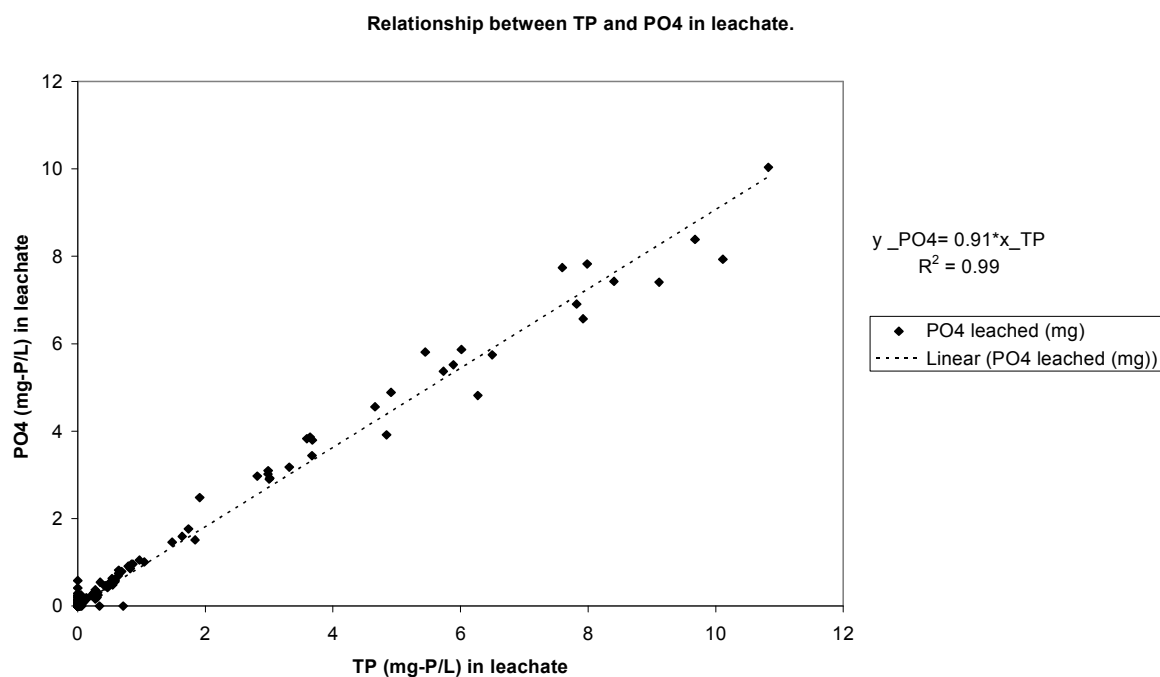


Figure 5 Relationship between TP and Phosphate in leachate.

P was measurable in the leachate only for columns fed continuously for both with high and low P solution. But as the 0.95 confidence interval is showing (Figure 6, big error bars); there was a great variability in the amounts of P-applied and also in the amounts of P-leached. The large errors bars for P applied are due to the delivery variability inherent to the pump and also showing differences in columns' infiltration rates as solution was ponding on surface, and these pondings periodically prevented time continuous application. Moreover, as cumulative data are showed here, the error from previous data is aggregated to the error of the actual data.

Mean Plot of multiple variables grouped by Date; categorized by P concentration and Application rate

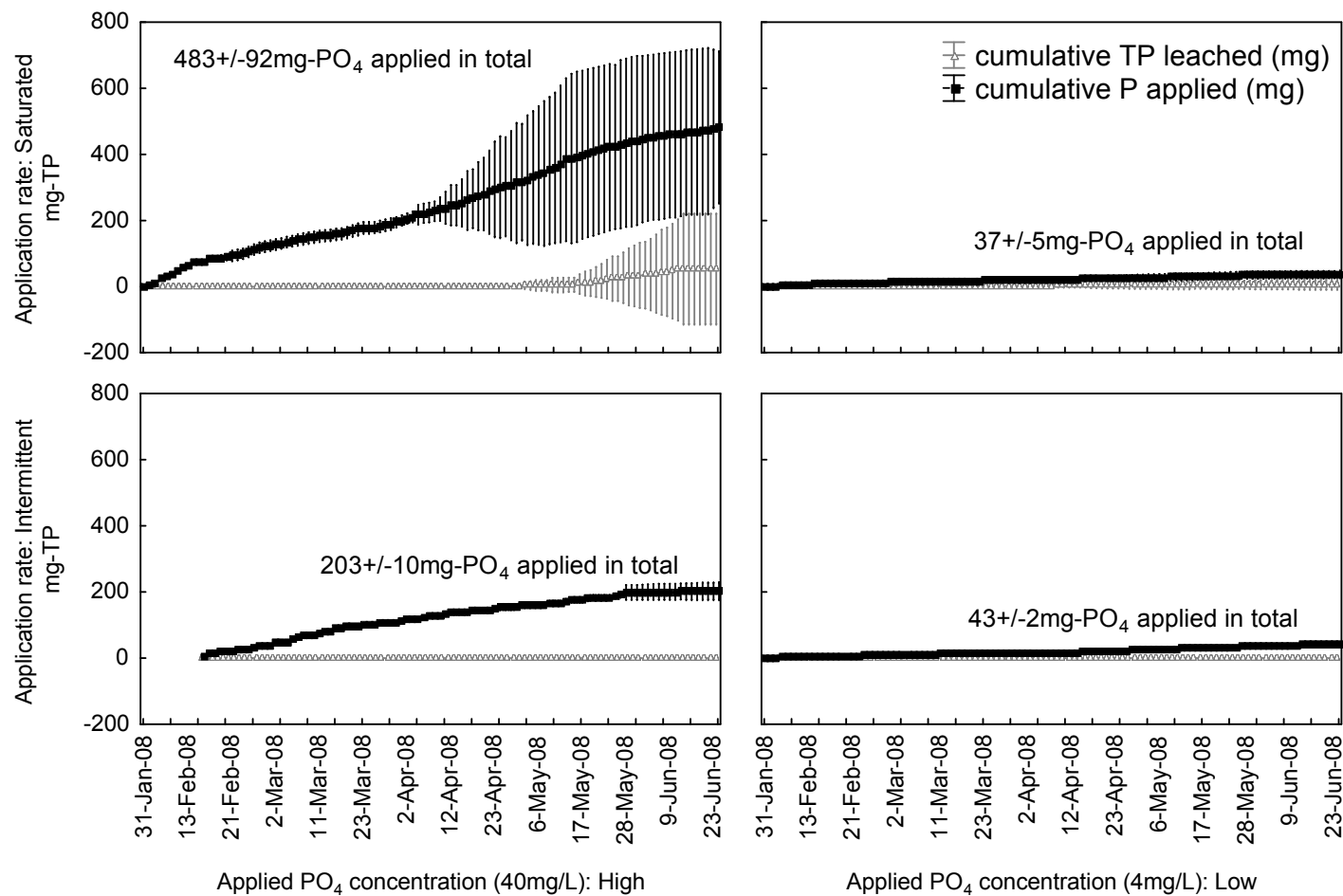


Figure 6 Evolution of Cumulative amount of P applied, and Total Phosphorus, TP in leachate from 31/01/08 until 24/06/08. (Vertical bars denote 0.95 confidence interval)

ANOVA on transformed data (log(TP)) identified significant effect of all the factors considered (Table 3)

Table 3 ANOVA table for cumulative TP leached (mg) (log) from columns fed with high and low P solution continuously or intermittently (bold when significant $p < 0.05$)

	Degree of Freedom	log(cumulative TP leached) - F	log(cumulative TP leached) - p
Intercept	1	500.83	0.00
Date(P concentration*Application rate)	206	1.52	0.00
P concentration	1	28.95	0.00
Application rate	1	979.70	0.00
P concentration*Application rate	1	12.90	0.00
Error	356		
Total	565		

Application rate and concentration of P in the feeding solution had significant effect separately on mean cumulative TP leached (mg). The interaction of application rate and concentration of P had also a significant effect on mean cumulative TP leached (mg) (Figure 7). The LSD table showed that application rate had a significant effect under both treatments high and low P. For intermittent application, concentration had a significant effect but not for continuous application. The amount of TP leached was significantly greater from low P fed columns than from high P fed columns. This is in accordance with (Mamo et al., 2005). In Mamo's study, when high P content soil was irrigated with low P concentration wastewater, then soil was desorbing P rather than adsorbing. Then, TP leached amounts were greater from saturated columns than intermittently fed columns. This is logical as when soil moisture increases, pH increases as well (Zarate-Valdez et al., 2006), then, carbonates will react more with Ca, making them less available to bind P, hence, P would desorb more (Morgan, 1996.).

Significant effect of the interaction between P application concentration and application rate
($p=0.000$)
Vertical bars denote 0.95 confidence intervals

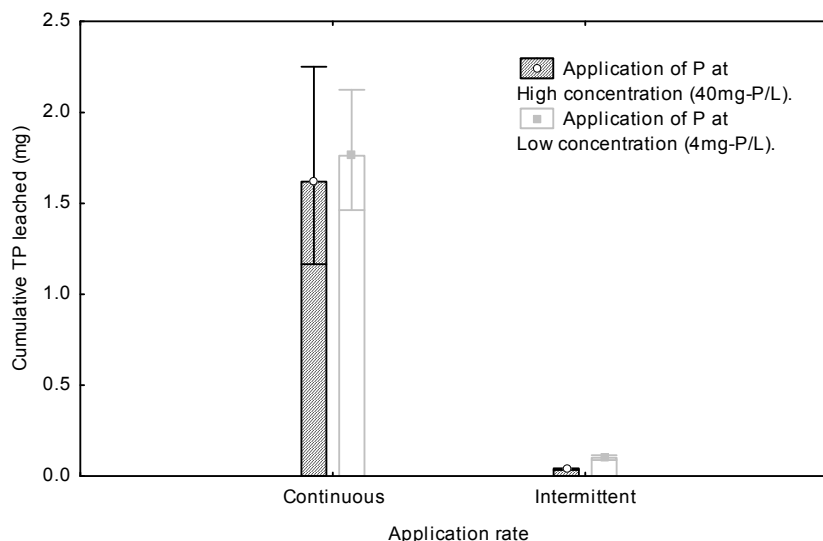


Figure 7 Mean Cumulative TP (mg) leached from columns fed with high and low P solution continuously or intermittently over the period of experimentation. Vertical bars denote 0.95 confidence interval.

P leaching pattern was discontinued as shown in Figure 8. The first time TP was detected, it was for a high P saturated column after 6 days of P application. But it took 45 days before this same column leached P again. High P intermittent columns started leaching P directly after the first applications but then stopped leaching for the subsequent 78 samplings. This revealed preferential flows conducting irrigation water directly during the first applications but then, probably because of clay swelling, P started probably to be adsorbed and not leached.

On saturated columns, both high and low P, the leached volumes followed the same patterns; the volumes leached increased progressively for 4 days and then dropped. This reflected the fact there was no irrigation on Sundays during the experiments. High TP concentrations corresponded to high volumes leached. This is in accordance with both pH and drainage theory; more irrigation induced more drainage, hence less contact then less adsorption and more irrigation induced increase in pH hence less Ca to adsorb P as well.

Mean Plot of multiple variables grouped by Date; categorized by P concentration and Application rate

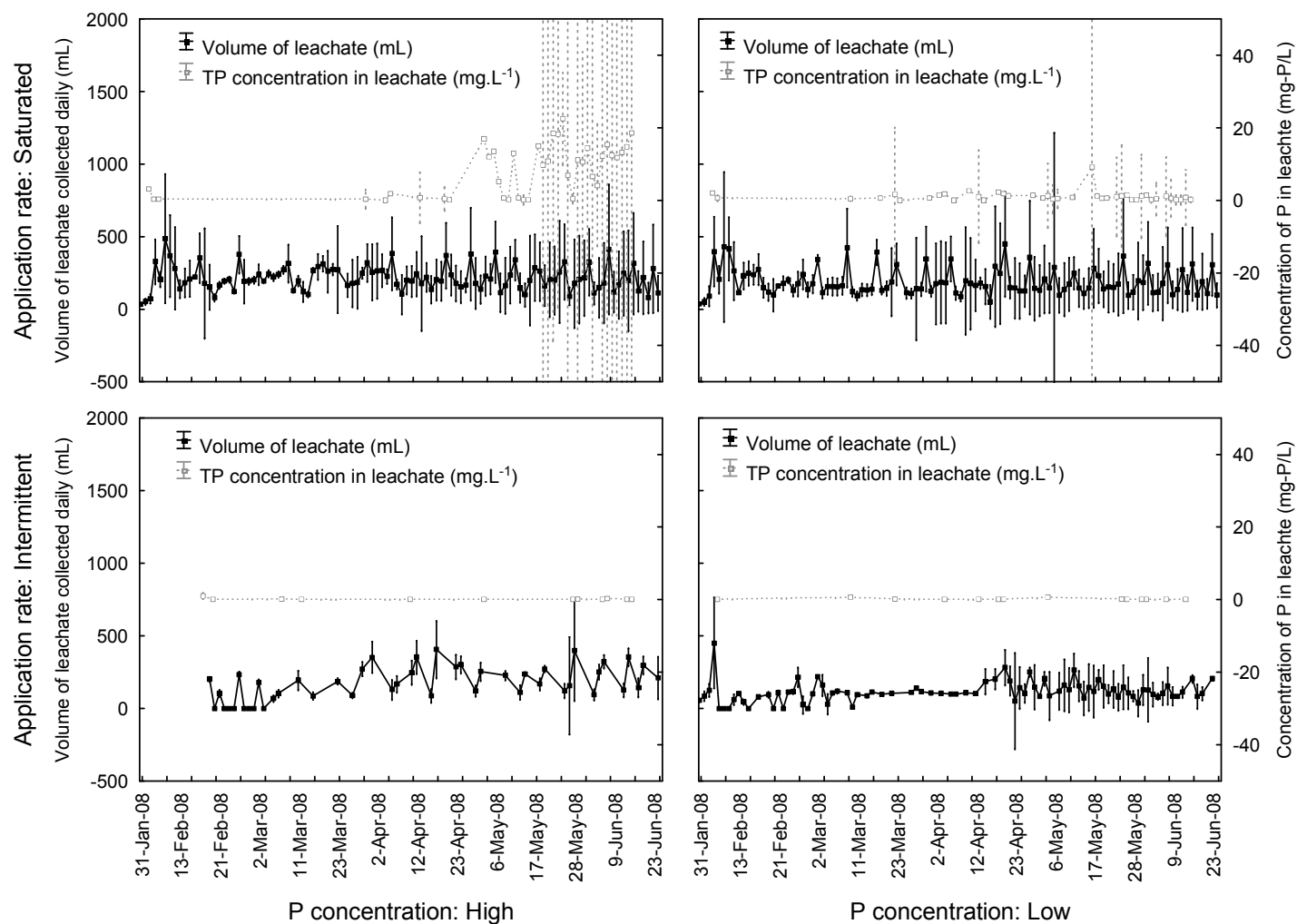


Figure 8 Evolution of volume of leachate and concentration of P in leachate as Phosphate (PO₄) and Total phosphorus (TP), in mg-P.L⁻¹ from columns fed continuous or intermittently with high concentrated P solution (40mg-P.L⁻¹) or low concentrated P solution (4mg-P.L⁻¹) (vertical bars denote 0.95 confidence interval)

As application rate and P applied concentrations were significant factors explaining the variations of P leaching out of the columns, the 4 cases, high, low P applied to maintain saturation, high, low P applied intermittently were considered in order to establish relationship between P applied and TP leached (Figure 9, representing each treatment with an automatic scale). Leaching patterns were different for each case; there was no fractal pattern identifiable (cf. Figure 9, 10, and 11).

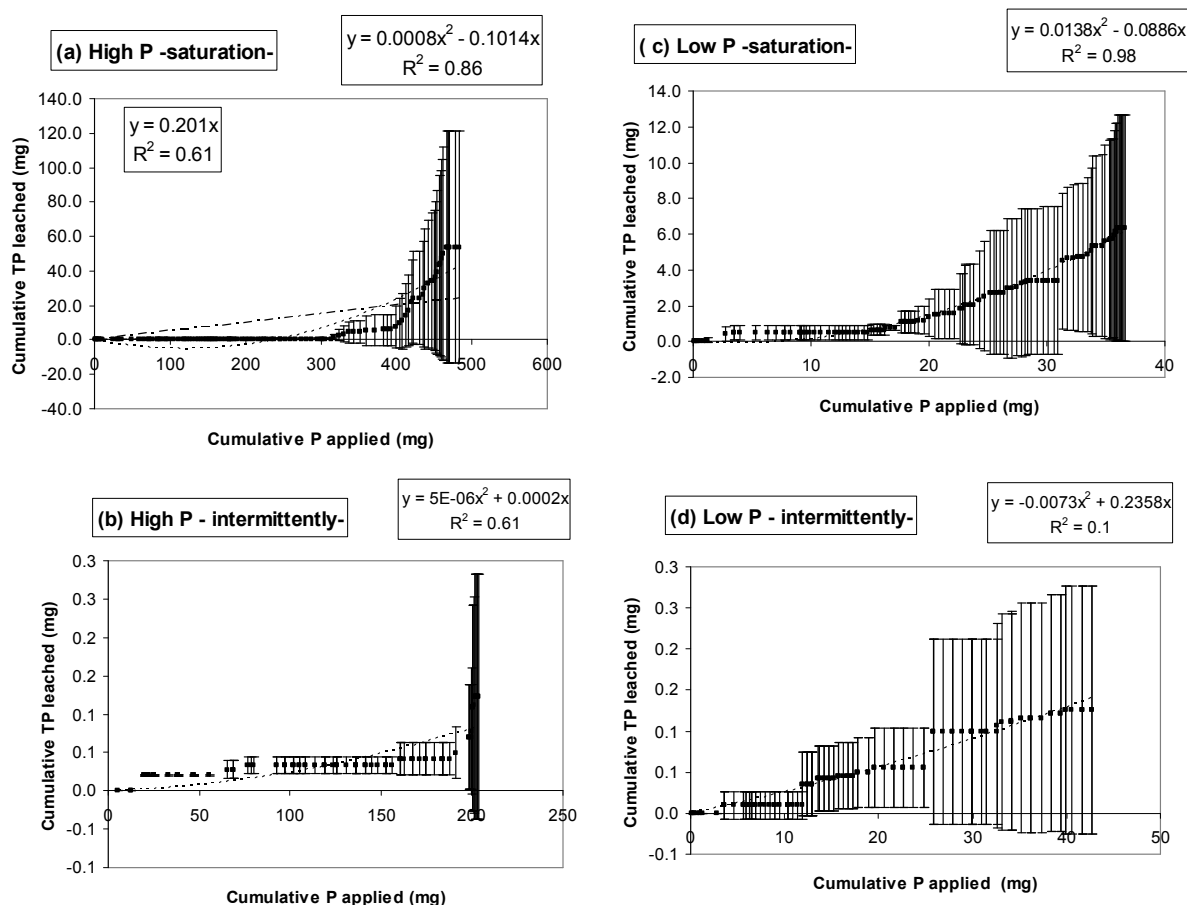


Figure 9 Evolution of the regression between cumulative amount of P applied (mg) and cumulative TP leached (mg) for the whole period of experiment under high, low P application to maintain saturation (a, c) and high, low P intermittent application (b, d) per date.

The different orders of magnitude of P leaching and application are noticeable (cf. Table 4)

Table 4 Comparison of maximum cumulative leaching P and maximum cumulative P applied for the 4 different treatments.

	<i>High P saturated</i>	<i>High P intermittent</i>	<i>Low P saturated</i>	<i>Low P intermittent</i>
Total cumulative P applied (mg)	483±92 mg	203±10 mg	37±5 mg	43±2 mg
Total cumulative TP leached (mg)	54±67 mg	0.1±0.1 mg	6.4±6.3 mg	0.1±0.1 mg
TP leached as % of TP applied	11.2	0.0	17.3	0.2

According to Table 4, while saturated, cumulative leached amount is around 1/5 of the cumulative amount applied, however, for intermittent application, the amount applied doesn't seem to be significant as high P columns received 4 times more P than low P columns but leached the same amount cumulatively. However, the concentrations appeared to be significantly important as for both application methods, low P fed columns leached more in % (17.3 % and 0.2 %) than high P fed columns (11.2 % and 0.0 %).

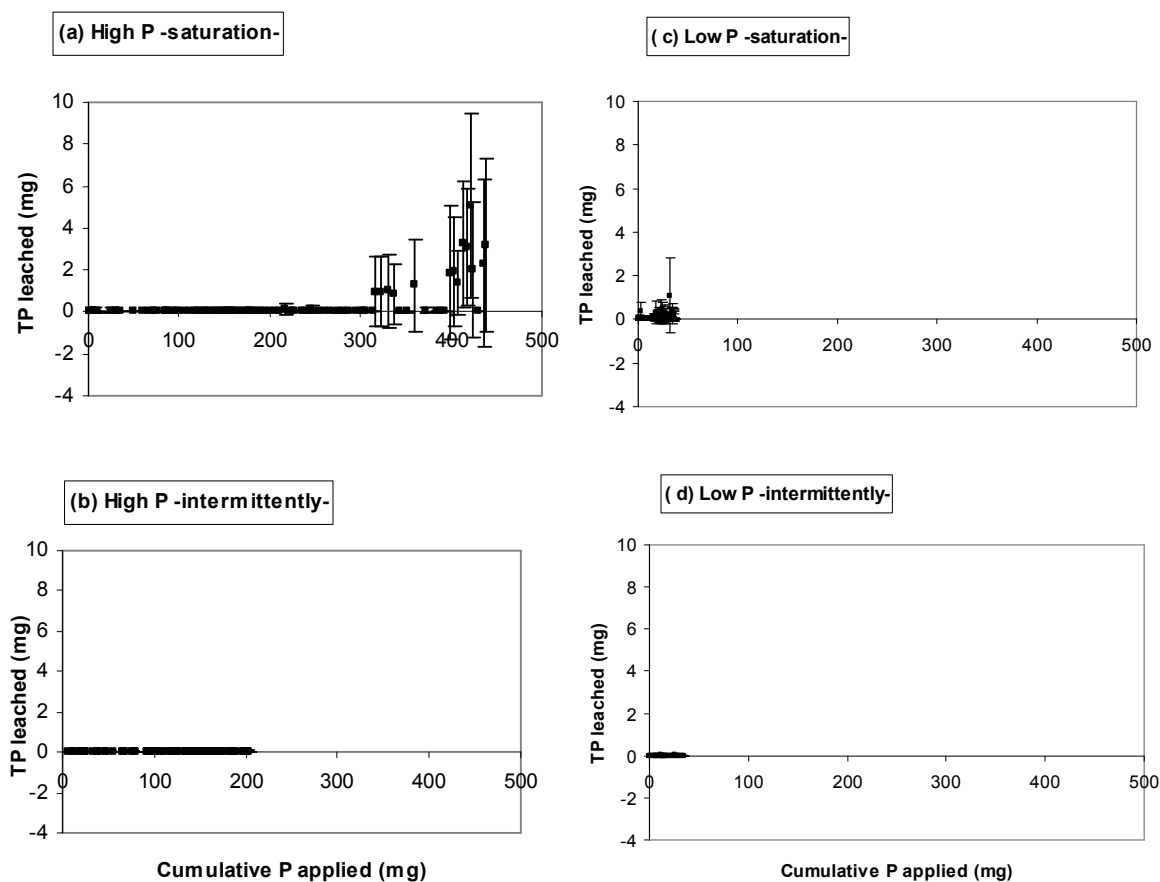


Figure 10 Evolution of mean TP leached (mg) in relation with cumulative P applied (mg) at a “big scale”

Figure 10 shows that the leaching patterns for the saturated columns are very different. For the same amount applied, the amounts of P leached by high P columns were lower than the amount of P leached by low P columns. And the patterns of P leaching on saturated high P columns were not constant but P was leached in peaks.

The scale was changed to observe how P leached on the other columns. Figure 11 (a zoom at a small scale to fit P leached from low P application) also that there was no constant pattern for P leaching from columns fed with low-P solution.

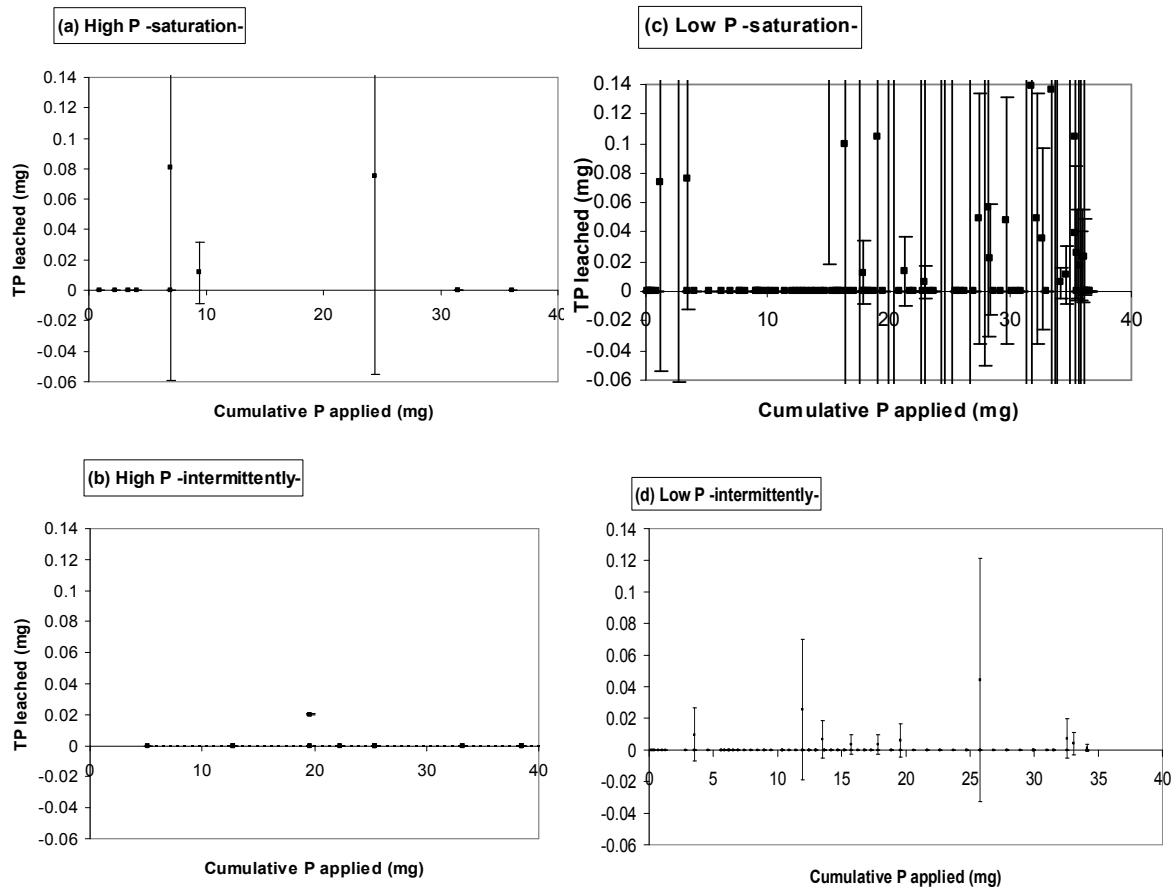


Figure 11 Evolution of mean TP leach (mg) in relation with cumulative P applied (mg) at a “small scale”

In order to model cumulative TP leaching compared to cumulative P applied by irrigation, different regressions were considered. However, the best description of all the relationships on figures 9 and 12 were stepped lines or a “tipping bucket” conceptual model. For a certain range of abscises; i.e. applied amounts of P, there is no leaching happening, the bucket is filling; with a steep TP leaching, the bucket is emptying, but then, for a following range there is no leaching at all, the bucket is filling again, etc. However, even though shapes were comparable, “steps” were very different from one graph to another and scales were adapted to each graph for more clarity. No fractal behaviour could be identified in particular (on comparing Figure 10, “big scale”, and 11, “small scale”), in other words, the different columns did not behave in the same way. Even comparing low against high P and the same application rate, or saturation against intermittent application for the same P concentration application, there is no pattern or link. Hence, a mathematical model cannot be fitted.

A conceptual model explaining this stepped leaching could be either a tipping bucket; once the bucket is filled, the bucket tips and empties its content, however, the difficulty to model this is the variation of the bucket volume at the end of each tipping. Moreover, according to (Heckrath et al., 1995), leaching would have been expected since P applied would have reached 91 mg. However, in none of the figures (a to d, Figure 9), 91 mg of P applied looked to be a trigger amount for P leaching. And leaching appeared before the 1006 mg-P were applied, value corresponding to Freundlich model estimated S_{max} . Hence both attempt to forecast P leaching failed.

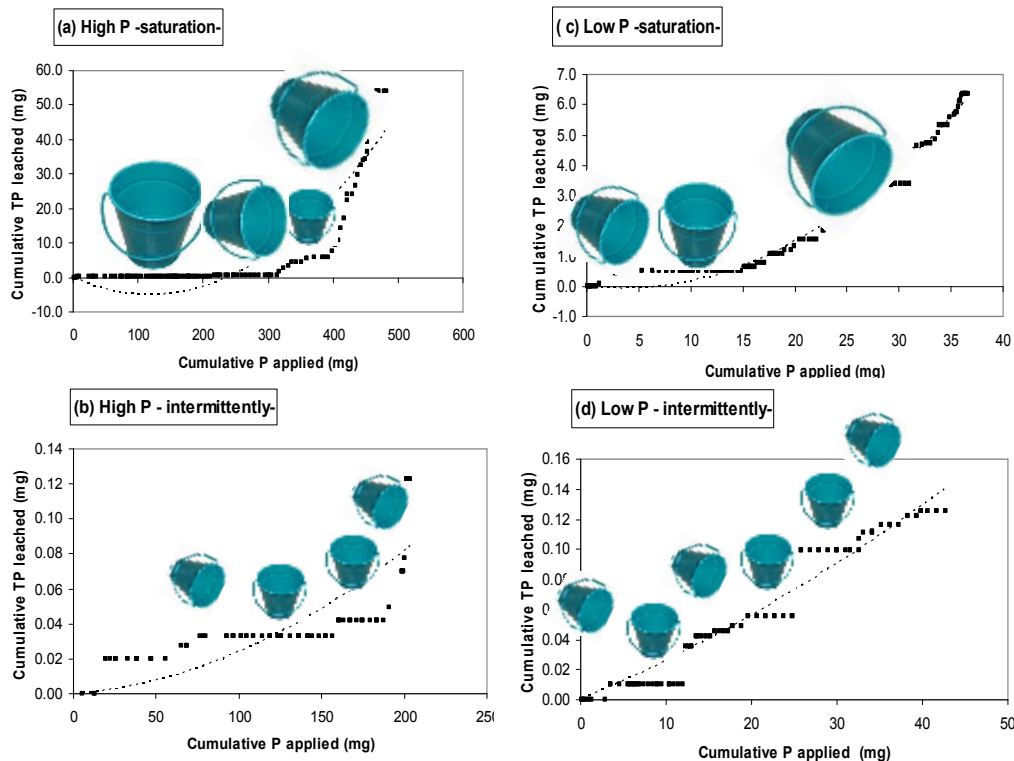


Figure 12 "Tipping buckets" conceptual model. The size of the buckets are different between treatments (low or high P concentrations feeding solutions applied at saturation rates or intermittently).

4.3 PHOSPHORUS DISTRIBUTION IN SOIL COLUMNS

4.3.1 Olsen-P distribution in soil column

ANOVA analysis concluded a significant effect of all the factors considered; depth, application rate and application concentration and interaction between the latter two factors (Table 5).

Table 5 ANOVA table for Olsen-P distribution. (Significant factors in bold)

	Degree of - Freedom	log(Olsen-P) - F -	log(Olsen-P) - p -
Intercept	1	4637.42	0.000
Depth (cat(application rate*P application))	16	30.40	0.000
application rate	1	11.67	0.002
P application	1	194.08	0.000
application rate*P application	1	14.95	0.000
Error	40		
Total	59		

Hence, after application of P as Phosphate, continuously or intermittently and at different concentrations, P migrated and was fixed in soil resulting in an heterogeneous distribution of Olsen-P in columns (Figure 13)

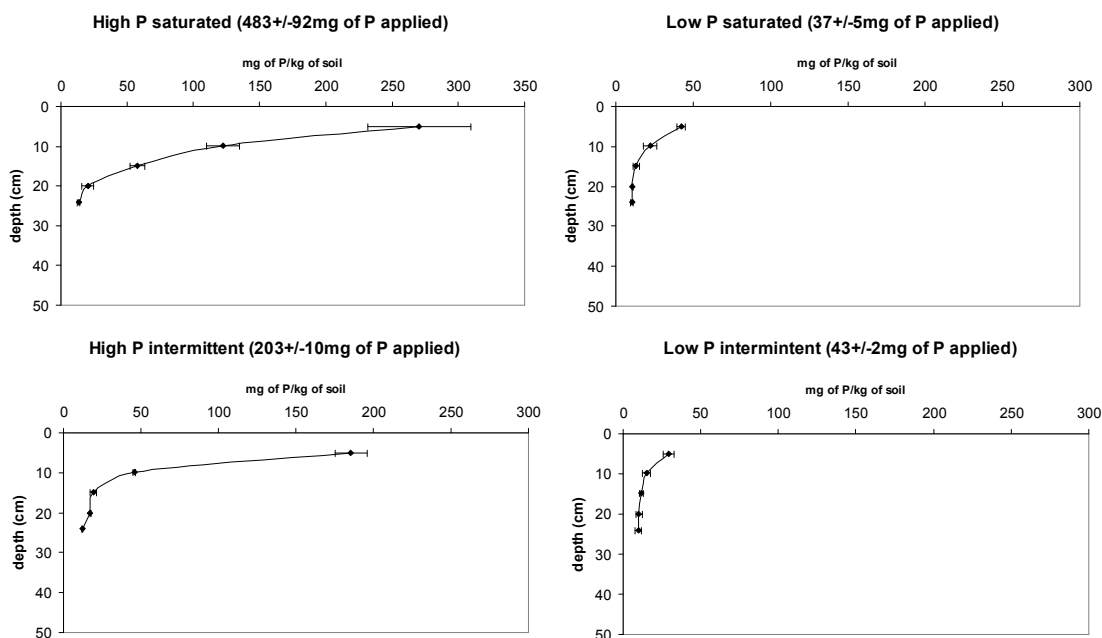


Figure 13 Olsen_P (mg-P) in soil profile after irrigation with phosphate solution (4 or 40 mg/L of phosphate) to maintain saturated conditions or intermittently. (---) Heckrath 60mg-P.kg⁻¹ of soil threshold.

As P is delivered by dripping on to the surface of the columns, higher concentration towards the surface was expected. All the columns presented the same pattern, progressive enrichment towards the surface. The relative increase of P in the top layer was proportional to the amount of P applied. The average Olsen-P for high P saturated columns' top layer, was 2, 6 and 10 times higher than for high P intermittent columns' ones, low P saturated columns' ones, low P intermittent columns' ones and the amount of P applied, 2, 10 and 12 times more respectively. LSD table analysis for depth factor revealed first, at all depths, the concentration of P feeding solution highly influenced Olsen-P. When fed with high P solution, Olsen-P build up was greater and there is a direct relationship between P added and subsequent Olsen-P. This means that more P was adsorbed as Olsen-P when the P concentration was greater. Second, neither concentration nor application rate had a significant effect on Olsen-P in the last layer (20-25 cm). In other words, there was no significant P adsorption as Olsen-P in this layer. Indeed, Olsen-P in the last layer remained under 10 mg.kg^{-1} ; therefore under Heckrath threshold of 60 mg.kg^{-1} for leaching. However, P leached out from the bottom of the columns and for this reason, it was expected to measure Olsen-P over Heckrath threshold on the whole profile and in particular at the bottom of the columns as well. This suggests that some preferential channel of P developed in this layer and P adsorption was minimised as it did not increase or change Olsen-P in the layer significantly (McGechan and Lewis, 2002; Mamo et al., 2005). Leaching was observed from all columns, however, there was no layer at or over Heckrath 60 mg-P.kg^{-1} in the low P fed columns, hence this threshold did not apply for Cranfield soil. Third, sustained application rate increased significantly Olsen-P compared to intermittent application but only for high P feeding and for the second and third layers (5-10 cm and 10-15 cm). This means that higher moisture content or more acidic condition were more favourable to Olsen-P adsorption. However, the significant increase happened for the second and third layers and not in the first. Because of increase in soil moisture, pH might have increased (Zarate-Valdez et al., 2006), however, P solutions were acidic, hence, in the lower layers, pH would be expected to be more acidic, hence more in favour of P adsorption by Ca (Morgan, 1996.). And finally, P application concentration has a significant effect on increasing Olsen-P in soil if continuously applied but not if intermittently. Again, this would be the equilibrium between P solution acidity itself and subsequent neutralisation because of greater soil moisture.

Therefore, from a WaterRenew system point of view or forecast of P leaching after P application by irrigation, Heckrath threshold appeared to have failed to forecast

precisely when P would leach from columns made with Cranfield chalky clayey soil. Indeed, P leached before the 60mg-P.kg^{-1} threshold was reached but in very low quantity (order of 0.1 mg-P.L^{-1}) for low P fed columns for both saturated and intermittent application rates and much more P can be added before greater concentrations of P start to leach. And P started leaching once at least one layer has reached 60 mg-P.kg^{-1} Olsen-P threshold but not the whole profile, for high P fed columns for both saturated and intermittent application rate. Hence, the appropriate way to use Heckrath threshold would be to use it only for the first 15 cm as once these depths would be saturated, P will leach through the whole profile of 25 cm.

4.3.2 Total phosphorus (TP) in soil column

ANOVA p-table revealed only depth and P application concentration had significant effect on Total Phosphorus (TP) distribution in columns.

Table 6 ANOVA table for TP distribution. (Significant factors in bold)

	Degree of - Freedom	TP_g.kg ⁻¹ - F -	TP_g.kg ⁻¹ - p -
Intercept	1	1403.57	0.000
Depth (cat(application rate*P application)	16	7.50	0.000
application rate	1	4.00	0.052
P application	1	33.67	0.000
application rate*P application	1	3.07	0.088
Error	40		
Total	59		

At the beginning of the experiment, columns were homogeneous and with the same TP content. There was at the end of the experiment significant differences in TP distribution with depths (Figure 14)

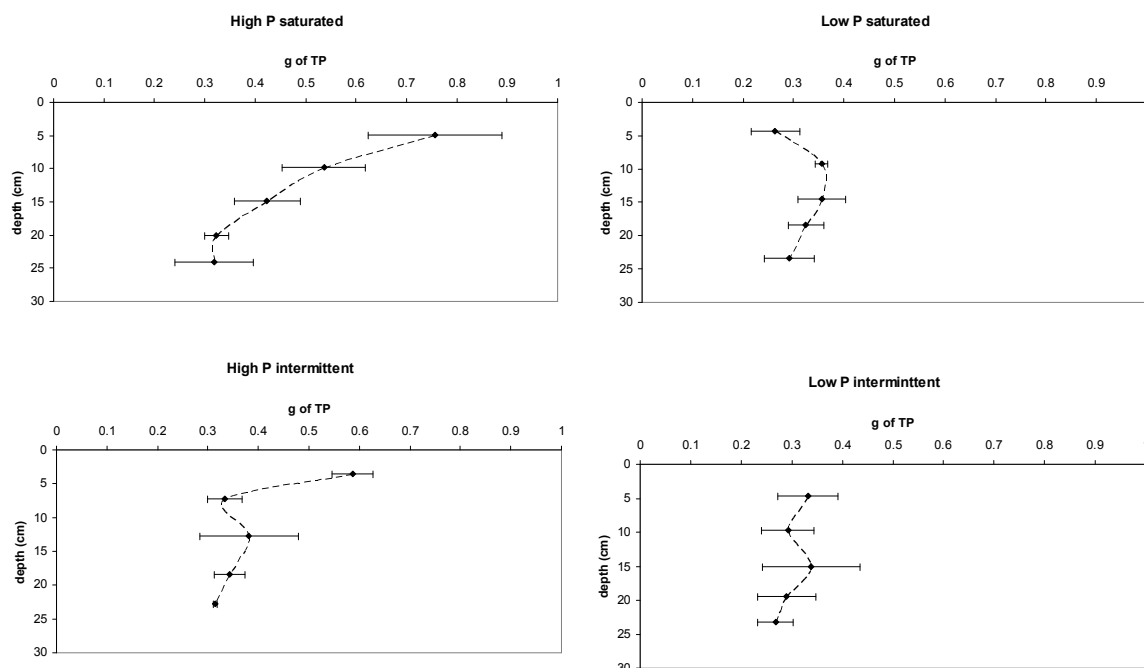


Figure 14 TP distribution (g of TP) in soil profile after irrigation with phosphate solution (4 or 40 mg/L of phosphate) to maintain saturated conditions or intermittently.

P was delivered by dripping on soil surface; hence an increase of TP gradually from surface to depth is expected. This is the pattern observed on high P loaded columns. On columns fed with low P, TP distribution is different; the highest concentrations are found in the middle of the columns rather than at the surface layer, but not significantly. For low P saturated columns, TP has the lowest concentration in the surface layer as if TP has been washed down. This is in accordance with (Mamo et al., 2005) pointing to the fact that when a too low P solution is applied, soil tends to lose P rather than adsorb it. However, it was not possible to confirm this with Freundlich isotherms. Mamo (Mamo et al., 2005) demonstrated that when P concentration in soil water is lower than the intercept of a linear regression on Freundlich adjusted data, then soil tends to desorb P rather than adsorb. But it wasn't possible to fit a linear regression on Freundlich adjusted data on our soil hence find this key P concentration in soil water and predict soil behaviour towards P.

Statistically, the way P was applied; saturated or intermittent, didn't have a significant effect on the way TP was adsorbed to soil matrix, in other words, soil moisture condition didn't influence significantly the way TP was adsorbed to soil matrix.

4.3.3 Relationship between P applied and Olsen-P build up in soil

As P guidelines in soil are generally given according to Olsen-P (RB 209, FAO 55), the relationship between P applied and Olsen-P build up in soil was investigated rather than TP build up.

All the data for all the columns were used together to establish this relationship (Figure 15).

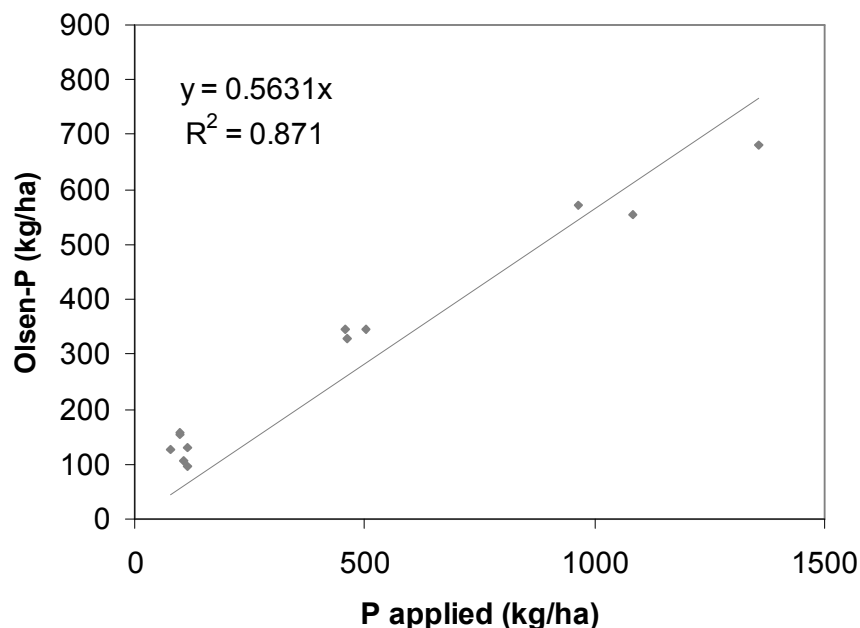


Figure 15 Linear regression P applied and Olsen-P built up in soil on an average layer of 60 cm depth.

The coefficient of determination for this regression is 0.87, hence close to 1 and the regression can be considered as good. Thus, 56% of P applied on soil as phosphates can be fixed as Olsen-P.

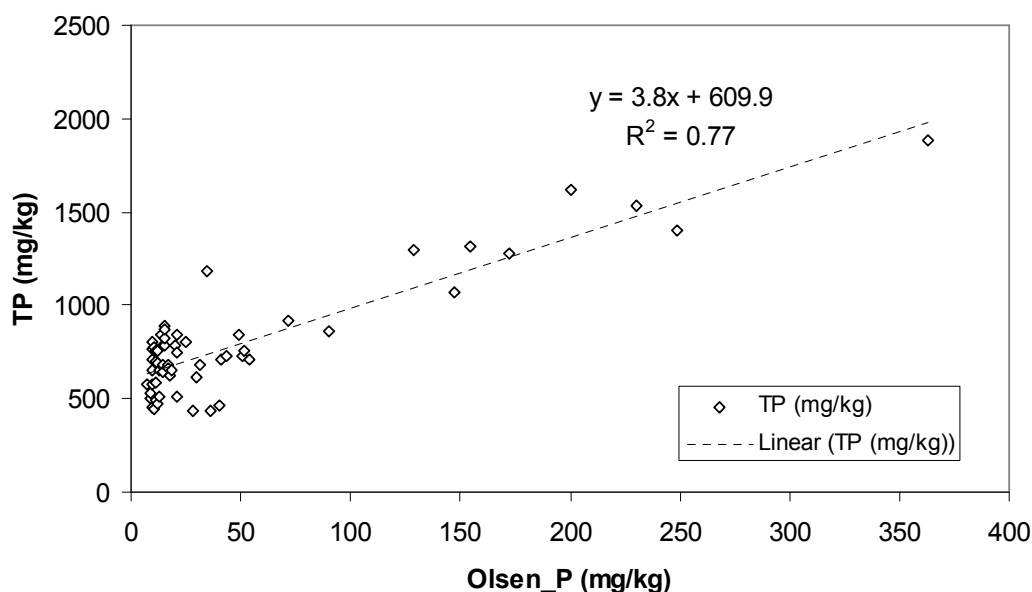


Figure 16 Relationship between Olsen-P and aqua regia TP. $TP = 3.8 \cdot Olsen-P + 609.9$ with $R^2 = 0.77$.

11 soils (loam, clay loam and silty clay loam) were studied for relationships between different forms of P present in soil, and in particular TP and Olsen-P (Allen and Mallarino, 2006). Cranfield soil presents 62 % of clay and none of the 11 soils had such a great amount of clay. The soil with the highest clay content was 37.5 % clay and the slope for TP and Olsen-P relationship of 4.9 and a coefficient of determination of $r = 0.95$. For the 11 soils, clay content ranged from 171 to 355 g.kg⁻¹ and slope from 3.1 to 5.1 with R^2 ranging from 0.55 to 0.95. Hence, the relationship calculated from this experiment (Figure 16) looks plausible. Figure 16 is showing that there is 610 mg.kg⁻¹ of TP initially in soil and Olsen-P represents 20 % of TP in soil. Hence, on combining Figure 15 and 16, 56 % of P applied becomes Olsen-P and this Olsen-P will contribute to 20 % of TP.

5. CONCLUSION

The aim of this chapter, by setting a disturbed column experiment, was to understand P leaching dynamics and the specific objectives of this chapter are to:

- **Objective 1:** identify, quantify and understand the fate of P applied in solution on a clayey soil (proportion immobilised, proportion leaching).

P leached under the form of phosphates, the same form under which it has been applied.

17.3 % of TP applied was leached from saturated low P concentrations columns, 11.2 % of TP applied was leached from saturated high P concentrations columns, 0.2 % TP applied was leached from intermittent application of low P concentrations columns and no P was leached from intermittent application of high P concentrations columns. Therefore, the remaining proportions of P applied accumulated in the soil.

- **Objective 2:** identify the effect of soil moisture on P leaching patterns.

Soil moisture has a significant effect on the amounts of P leached; P leached more from saturated columns than from columns with lower soil moisture even when P was applied at low concentrations.

- **Objective 3:** identify the effect of the concentrations at which P is applied on P leaching patterns.

The concentrations at which P is applied has a significant effect on the amounts of P leached; when the averages of P leached were considered, on average more P leached from columns fed with high P solution than from columns fed with low P solution.

However, on saturated application, the concentration of P in the feeding solutions didn't significantly influence the average amounts of P leaching from the columns.

- **Objective 4:** develop a relationship between P applied and P leached or a relationship between P applied and P immobilised in soil to help forecasting P leaching.

P leaching patterns were "stepped" and the conceptual model explaining leaching patterns was a tipping bucket. However, the size of the bucket was variable and the variation not predictable. Hence, it was not possible to model P leaching

patterns. But it was possible to model how P applied on soil as phosphate in solution would be incorporated in the soil P pool and be counted as Olsen-P with a good correlation ($P_{\text{applied}} (\text{kg} \cdot \text{ha}^{-1}) = 0.56 \cdot \text{Olsen-P} (\text{kg} \cdot \text{ha}^{-1})$ with $R^2 = 0.87$). This value will be used in WR_MODEL to forecast when the upper layer of soil of the site studied will reach Heckrath Olsen-P threshold while irrigated with effluent. This study demonstrated this threshold failed to forecast P leaching but as it is very simple, it was still used as a benchmark.

Then the following hypotheses were formulated at the beginning of the experiment:

- Hypothesis 1) for comparison between columns maintained at saturation by being fed with high and low P solutions : It is expected to observe P leaching faster from columns fed with the high P feeding solution than from columns fed with the low P feeding solution.

This hypothesis was verified.

- Hypothesis 2) for high P intermittent application: The apparition of bypass flow paths will result in P leaching out of the system before reaching soil P maximum capacity in the column. (Thomas et al., 1997)

This hypothesis was not verified. With the amounts applied, there was no significant leaching observed. 203 mg of P was effectively applied on these columns. Before the experiment, the forecasted amount of P to add to bring Olsen-P up to 60 $\text{mg} \cdot \text{kg}^{-1}$, Heckrath threshold, was 91 mg. However, after the experiment, it was found that only 56 % of applied P participated to Olsen-P built up, therefore, a total of 163 mg of P had to be added to bring Olsen-P up Heckrath threshold. So it was unexpected not to see P leaching from these columns.

- Hypothesis 3) for comparison between columns fed with low P solutions at saturation or intermittently: P sorption in saturated conditions is greater than in unsaturated conditions when applied at the same concentration on the feeding water as contact time will be greater.

This hypothesis was verified. The same amount of P was applied to low P fed columns and 98.9 mg of Olsen-P were measured in the low P saturated columns and 76.0 mg of Olsen-P were measured in low P intermittent. 30 % more Olsen-P was sorbed in saturated columns than in non-saturated columns and Olsen-P accumulated significantly in the first 3 layers (15 cm depth).

Thus, this experiment demonstrated the following points:

- Heckrath Olsen-P threshold of 60 mg.kg^{-1} did not apply to Cranfield chalky clay soil.
- Soil moisture is very important on controlling P leaching, and in particular, on a field application point of view, water logging should be avoided even when soils are irrigated with low P solutions as P will start to leach.
- It is difficult to model P dynamics with simple equations and more studies are required.

6. REFERENCES

- Allen, B. L. and Mallarino, A. P. (2006), "Relationships between Extractable Soil Phosphorus and Phosphorus Saturation after Long-Term Fertilizer or Manure Application", *Soil Science Society of America Journal*, vol. 70, no. 2, pp. 454-463.
- Djodjic, F., Borling, K. and Bergstrom, L. (2004), "Phosphorus Leaching in Relation to Soil Type and Soil Phosphorus Content", *Journal of Environmental Quality*, vol. 33, no. 2, pp. 678-684.
- Gibson, C. E. (1997), "The Dynamics of Phosphorus in Freshwater and Marine Environments", in Tunney, H., Carton, O. T., Brookes, P. C., et al (eds.) *Phosphorus Loss from Soil to Water*, CAB international, UK, pp. 119-135.
- Heckrath, G., Brookes, P. C., Poulton, P. R. and Goulding, K. W. T. (1995), "Phosphorus Leaching from Soils Containing Different Phosphorus Concentrations in the Broadbalk Experiment", *Journal of Environmental Quality*, vol. 24, no. 5, pp. 904-910.
- Hooda, P. S., Rendell, A. R., Edwards, A. C. and Withers, P. J. A. (2000), "Relating soil phosphorus indices to potential phosphorus release to water.", *Journal of Environmental Quality*, vol. 29, ., no. no. 4 (July 1), pp. 1166.
- MAFF, (2000), *Fertiliser recommendations for agricultural and horticultural crops (RB209)*, Seventh edition ed., the stationary office, London, UK.
- Mamo, M., Gupta, S. C., Rosen, C. J. and Singh, U. B. (2005), "Phosphorus leaching at cold temperatures as affected by wastewater application and soil phosphorus levels", *Journal of Environmental Quality*, vol. 34, no. 4, pp. 1243-1250.
- McGechan, M. B. (2002), "SW--Soil and Water: Sorption of Phosphorus by Soil, Part 2: Measurement Methods, Results and Model Parameter Values", *Biosystems Engineering*, vol. 82, no. 2, pp. 115-130.
- McGechan, M. B. and Lewis, D. R. (2002), "SW--Soil and Water: Sorption of Phosphorus by Soil, Part 1: Principles, Equations and Models", *Biosystems Engineering*, vol. 82, no. 1, pp. 1-24.

- Morgan, J. J. (1996.), *Aquatic chemistry : chemical equilibria and rates in natural waters*. 3rd ed. John Wiley & Sons, New York, NY.
- Murphy, J. and Riley (1962), "A modified single solution method for the determination of phosphate in natural waters.", *Anal. Chim. Acta*, vol. 27, pp. 31-36.
- NSRI (2008), "Soils site report (Full soil report)", .
- Olsen, S. R., Cole, C. V., Watanabe, F. S. and Dean, L. A. (1954.), "*Estimation of available phosphorus in soils by extraction with sodiumbicarbonate*.", *USDA*, vol. Circular 93., pp. 1-19.
- Persson, M. and Berndtsson, R. (1998), "Estimating transport parameters in an undisturbed soil column using time domain reflectometry and transfer function theory", *Journal of Hydrology*, vol. 205, no. 3-4, pp. 232-247.
- Pierzynski, G. M. (2000), "*Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters*", *Southern Cooperative Series Bulletin*, vol. 396, pp. 102.
- Rowell, D. L. (1994), *Soil science : methods and applications*, Longman Scientific & Technical, Harlow.
- Thomas, D., Heckrath, G., Brookes, P. C., Carton, O. T., Johnston, A. E. and Cab International, W. (1997), "Evidence of Phosphorus Movement from Broadbalk Soils by Preferential Flow", *In: Phosphorus loss from soil to water*, , pp. 369-370.
- Torrent, J. and Delgado, A. (2001), "Using Phosphorus Concentration in the Soil Solution to Predict Phosphorus Desorption to Water", *Journal of Environmental Quality*, vol. 30, no. 5, pp. 1829-1835.
- Van der Zee, S. E. A. T. M. and van Riemsdijk, W. H. (1988), "Model for long-term phosphate reaction kinetics in soil.", *Journal of Environmental Quality*, vol. 17, no. 1, pp. 35-41.
- Zarate-Valdez, J. L., Zasoski, R. J. and Lauchli, A. E. (2006), "Short-term effects of moisture content on soil solution pH and soil Eh. ", *Soil Science*, vol. 171, no. 5, pp. 423-431.
- Zhou, M. and Li, Y. (2001), "Phosphorus-Sorption Characteristics of Calcareous Soils and Limestone from the Southern Everglades and Adjacent Farmlands", *Soil Science Society of America Journal*, vol. 65, no. 5, pp. 1404-1412.
- Zou, X., Binkley, D. and Doxtader, K. G. (1992), "A new method for estimating gross phosphorus mineralization and immobilization rates in soils", *Plant and Soil*, vol. Volume 147, no. 2, pp. 243-250.

CHAPTER 9 : MODELLING FRAMEWORK: WATERRENEW SYSTEM DESIGN AND DECISION SUPPORT TOOL

1. INTRODUCTION

A WaterRenew system is a system where wastewater polishing is coupled with fast growing wood crops production.

The advantages of such a system may be environmental, social and economical but the system needs to be operating without any or minimum risks of pollution. These risks can be contamination of soil (cf. heavy metals, salinisation, pathogens), or pollution of groundwater or surface water with leaching of wastewater with an unsatisfactory level of treatment. Those risks will result from inappropriate operation of such a system (e.g. inappropriate application rate, volume applied, frequency). In theory, if a system is big enough, i.e. irrigation rates are low enough, then, any level of treatment can be achieved. Therefore, for a given location (soil and climate), with a given wastewater treatment work (volume and quality of effluent), in order to prevent any risk, there is a need for a tool able to predict the minimum area necessary to cultivate with trees to treat a given volume of effluent.

As this technology is not new and on commercial use in Australia (Myers et al., 1999), Sweden (Aronsson et al., 2000) and the USA (Paranychianakis et al., 2006), such tools do exist, one in particular: WATLOAD2, a model to dimension an effluent irrigated Eucalyptus plantation in Australia and WATCOST to assess economical benefit from such a plantation, both developed by Myers et al (Myers et al., 1999).

However, because a WaterRenew system is a soil vegetated based wastewater treatment system, its operation and performances highly depends on edaphic and climatic conditions. Therefore, as first, WATLOAD2 is calibrated for Australian bioclimatic zones, second, it is calibrated for eucalyptus tree only and third, neither EU nor British regulations are taken in account to calculate the minimum area to cultivate to set a sustainable system, WATLOAD2 cannot be used to design a WaterRenew system in the UK.

Thus in order to help the design and estimate the feasibility of the implementation of a WaterRenew system under UK specific climato-edaphic conditions and regulations, using 2 endemic tree species, poplar and willow and one tropical, eucalyptus, the

following model WR_MODEL was developed. WR_MODEL presents similar degree of complexity than WATLOAD2 and use a similar conceptual framework than WATLOAD2. WR_MODEL integrates a cost benefit tool which is independent from WATLOAD2 (Myers et al., 1999). WR_MODEL attempts also to take in account P and Na accumulations in soil but it only assesses if there is a risk of un-sustainability in the first 30 years of exploitation.

This model should be a Decision Support tool able to answer two questions: for any specific conditions of any specific site (soil type, effluent quality, climatic conditions, trees selected)

1. How big does a WaterRenew system need to be to be sustainable on a specific site?
2. How much would it cost to implement an optimised area of WaterRenew system and irrigation reservoir?

These questions will be answered based on the sustainability of wastewater irrigation, accepted “permeability¹” of the system, the compliance with existing regulations, tree yields boosting and wood production and land availability.

This model is designed to be used by wastewater treatment professionals. As it can assess the size and cost for implementing such a system, it can help in the decision making process once this technology is considered. For this purpose, the model is an excel spreadsheet and user-friendliness was always considered during its elaboration.

¹ A WaterRenew system can be designed to be completely permeable, i.e. the amount of irrigation is set to prevent irrigation induced drainage. It can also be set to allow some irrigation induced drainage.

What WR_MODEL does?

- For a specific site with specific climato-edaphic and effluent characteristics and a chosen tree species, it will give an **estimate** of the optimised area to be cultivated as well as the surface of the irrigation reservoir to be built.
- It will give an estimation of the initial investment necessary to establish both cultivated area and reservoir. It also gives an **estimation** of the cost to treat either 1 tonne of N or 1 tonne of P which can be compared to conventional costs. It will provide an estimation of the benefit the sale of trees can bring and also net income estimation for a 30 years exploitation and the number or years after which the initial investments can be recovered.

What WR_MODEL does not do?

- WR_MODEL does not forecast wastewater efficiency and does not provide any information on soil water quality at any stage of the treatment.
- It can not guarantee treatment efficiency.
- It does not consider nor predict behaviour for pathogens or heavy metals.
- It gives only an estimation of the sustainability of the system because P and Na accumulations are calculated with specific parameters for Cranfield chalky clay soil.

Moreover, WR_MODEL was calibrated with data from the Cranfield University field trial where wastewater polishing using willow, poplar and eucalyptus has been monitored and assessed (details on experimental settings are described in Chapter 3). The field trial gave the assurance a WaterRenew system can work efficiently and provided constants to describe each compartment's (soil, soil water and tree) behaviour to wastewater application. Indeed, crop factors, nutrient content and yield evolution for each tree species were made available in Chapter 4; soil evolution to wastewater application and tree cultivation in Chapter 5, the sodium story from effluent to soil in Chapter 7 and the specific case of phosphorus evolution in soil in Chapter 8. In effect, this model is an integrating tool to link together all the data, observation and understandings on processes gathered on the field trial.

The specific objectives of this chapter were:

- **Objective 1:** to present, describe and explain this design and decision making tool for a WaterRenew system, WR_MODEL.
- **Objective 2:** to verify (there were not enough data to validate the model) on running another set of data and conduct a sensitivity analysis to identify the sensitivity of the models to its parameters.

2. CONCEPTUALISATION

2.1 MODEL DEFINITION

The model will be articulated in two parts (Figure 1):

- a first part (technical) with a combination of sub-models calculating the minimum area to cultivate a WaterRenew system on the specific site to achieve sustainable wastewater tertiary treatment and tree production , cf. rearranged WATLOAD2 (Myers et al., 1999)
- and then a second part (decision making) will assess the feasibility from an economical point of view, for the sustainable system defined by the outputs of the first part calculating cost (the sum of capital cost and maintenance cost defined as 10% of the capital cost, (Urgun-Demirtas et al., 2008) for a chosen “permeability” of the system or degree of tolerated irrigation induced drainage.

2.2 MAIN PRINCIPLES

First of all, the scope of this model is limited. It considers only a simplification of processes happening when a SRC is irrigated with effluent as it effectively considers them only in one dimension and in a homogeneous layer of soil defined from surface to root zone depth at a monthly time step.

The model can be described as a combination of a simple water balance and nutrient balance. The water balance is a one-dimensional monthly water balance model evaluating soil moisture content around the root zone according to climatic conditions and water management. The water balance is modelled as a simple 1D “bucket” model. Hence, it has a limited capacity and once this volume is reached (Field Capacity, FC), any additional water drains or runs off.

Specific regulations for irrigation with effluent are not available yet. For this reason, the treated effluent applied was considered as organic manure according to the classification of RB 209 (MAFF 2000) and its recommendations are integrated in the model. Indeed, RB 209 was developed by MAFF² to advise farmers with the optimum amounts of fertiliser necessary to apply to get the best cost-effective return. Irrigation with effluent is bringing nutrients to the system, hence potentially, nutrients could leach. It appears then important to consider the potential vulnerability of a site to nutrient leaching before hand. For this reason, Nitrate Vulnerable Zone action plan (Great Britain. Parliament. Joint Committee on Statutory Instruments. et al., 2008) will also be integrated in the model and prevent any risk of nutrient leaching and subsequent eutrophication or nitrates contamination of surface or groundwater.

Hence, the simplified water balance is equilibrated in order to provide monthly irrigation rate with the constraint to prevent nutrient leaching. As the volume of effluent to be treated is known, a minimum area to be cultivated as a WaterRenew system on a specific site can be calculated. This minimum area would have been constrained only hydrologically at this stage. The hydrological focus on the model building can be justified by the ways a WaterRenew system can fail. It can failed by 2 ways; i) by not removing satisfactory amounts of N and P from effluent applied by irrigation and ii) by allowing drainage and runoff of effluent without any N and P removal. But both failures can be controlled by irrigation rate; i) by irrigating amounts of effluent so in accordance with site specific nutrient removal capacity (cf. soil initial nutrient composition, P sorption capacity, salinity), and ii) by irrigating amounts in accordance with site hydraulic characteristics (infiltration rate, field capacity).

Therefore, the amounts of nutrients authorised to be applied (for N, nitrogen) and at the same time preventing salinisation or accumulation of salt in the root zone are limited. They are calculated with the minimum area defined at the previous step. Hence, this iterative process carries on until all constraints (hydrological and nutrient) are met.

Once the minimum area is determined, the period of time the WaterRenew system set can function sustainably will be assessed by the time necessary for soil to build up Phosphorus to a level soil might be feared to leach P (Brookes et al., 1997). However, P leaching forecast as soil water quality won't be modelled.

² MAFF: the Ministry of Agriculture, Fisheries and Food was dissolved by the Order 2002 (S.I. 2002/794) and replaced by the Department of Environment, Foods and Rural Affairs from 2001.

In theory, if the effluent irrigation rate is appropriate and matches the climato-edaphic conditions of a site, the risks associated with a WaterRenew system should be avoided. The latter are contamination of soil (cf. heavy metals, salinisation, pathogens), or pollution of groundwater or surface water with leaching of wastewater with an unsatisfactory level of treatment (Chapter 2). The view adopted in this model in order to maximise irrigation rate, is that if a system is maintained to field capacity, there should not be any irrigation induced drainage but there will be a rainfall induced drainage taking place at the beginning of a rainfall event. The user is given the option to chose the % of irrigation induced drainage or runoff. There are 3 approaches:

- Irrigate to maintain soil moisture under field capacity to avoid rainfall induced drainage. This approach has the advantage to limit the risk of leaching of bad quality soil water/effluent mix. But to reach zero drainage, soil moisture should be always lower than the maximum rainfall intensity per day. And depending on the variability of rainfall intensity, considering this approach might reduce considerably the rate of irrigation. This will impair strongly the feasibility of this WaterRenew system as much more land will be required to irrigate the totality of the effluent produced at the sewage treatment work.
- Irrigate to maintain soil moisture at field capacity. The solution when irrigating with a salinisation risky effluent or soil is to “over” irrigate and provoke leaching of salts under the root zone (Westcot et al., 1985.; Westcot, 1988). If irrigation is calculated on taking in account this leaching requirement, once the system will be at equilibrium, irrigation will induce a permanent leaching. Therefore, there will be a risk of leaching a mix of soil water and effluent with an unsatisfactory quality. And this will impair strongly the sustainability of this WaterRenew system.
- Irrigated to maintain soil moisture slightly over field capacity. This approach increases the risk of leaching a mix of soil water and effluent with an unsatisfactory quality into groundwater. Chapter 7 proved soil relative importance on removing nutrients to be very important. Depending on the rate of irrigation and drainage induced, and if the water table is deep enough, this induced drainage can become leaching requirement (Westcot et al., 1985.; Westcot, 1988) and prevent salinisation and there might be enough soil depth to remove efficiently N and P from the soil water/effluent mix. If the water table is deep enough, and the drainage induced small enough, this approach might

not impair the sustainability of the system and increase its feasibility as the area required to irrigate the totality of the effluent produced at the sewage treatment work will decrease. But the results of a P leaching column experiment with different soil water content in columns demonstrated that soil moisture content had significant effect on P leaching patterns (Chapter 8). A waterlogged soil will leach P even with low P loadings but 10-fold greater P loadings; if soil moisture content is maintained close to field capacity then the same soil will not leach P.

As Therefore the second and third approaches were considered more closely in this model.

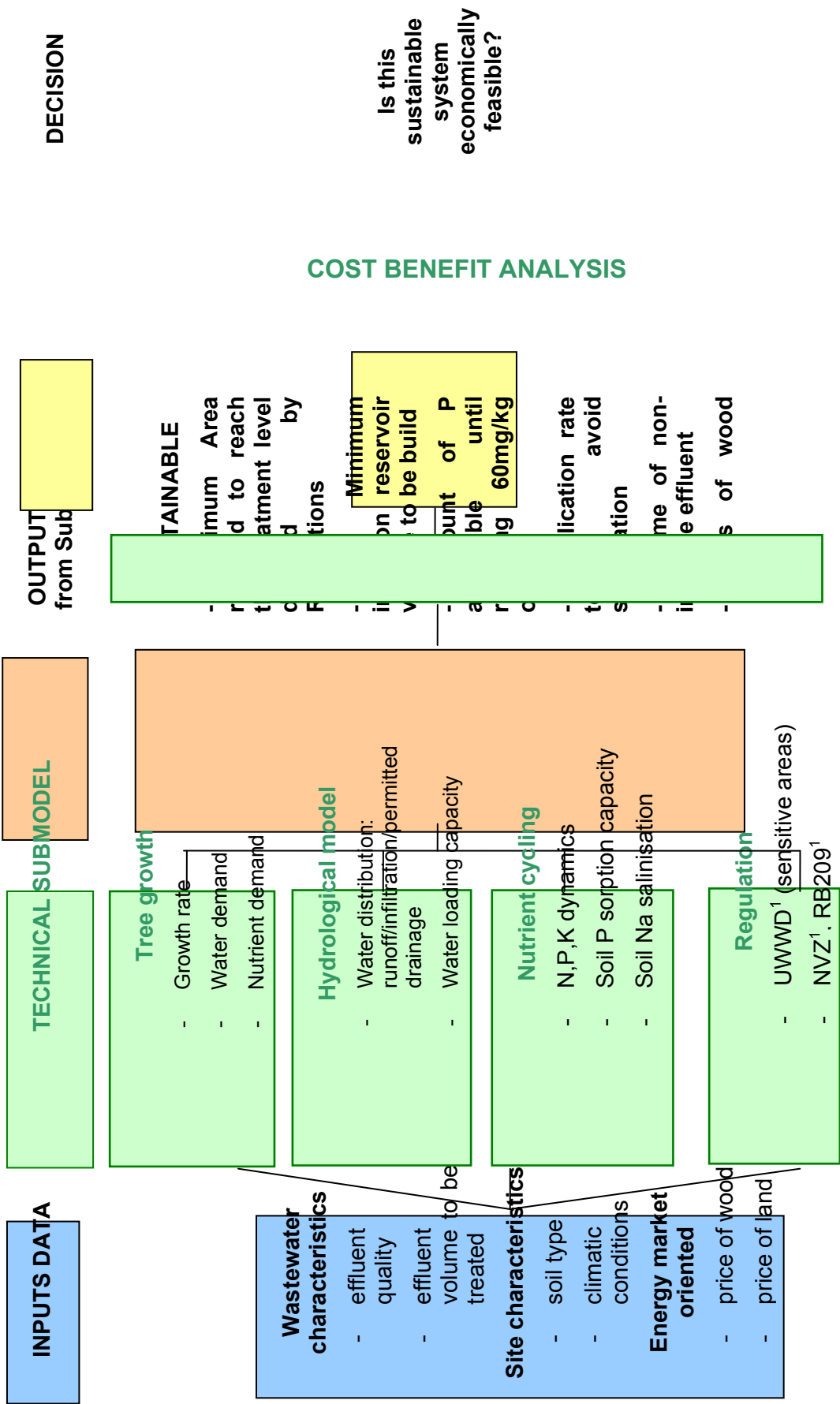


Figure 1 Conceptualisation of the WaterRenew design and decision support tool (¹:GB, 2008)

3. MODEL DESCRIPTION

3.1 SOIL WATER BALANCE IN WR_MODEL

Soil water balance was calculated to fulfil water mass conservation and energy in the system, on considering it as one-dimensional from one layer of soil, from surface to a depth d (m).

$$ET + Interception + Drainage + Runoff = -\Delta WS + Rainfall + Irrigation$$

Equation 1 Water balance model from soil surface to a depth d (m), ET , evapotranspiration (mm), Interception, fraction of Rainfall intercepted by leaves and not reaching soil (mm), Drainage (mm), Runoff (mm), Rainfall (mm), Irrigation (mm), $-\Delta WS$ (mm), variation of soil water storage (mm).

Evapotranspiration is calculated according to FAO Penman-Monteith (Allen, 1998.).

In a WaterRenew system, a major assumption is followed:

- Constant soil moisture content once field capacity is reached.

The irrigation rate is set to maintain soil moisture content equal to field capacity¹. This setting allows a maximum effluent delivery but at the same time, minimise loss of water out of the system by drainage or runoff. Hence, once soil moisture content is brought to field capacity, its fluctuations should be minimised (Equation 2).

$$\text{If } SW = FC \text{ then } -\Delta WS \approx 0$$

Equation 2 Assumption of constant soil water content (SW, %) once soil moisture has reached field capacity (FC, %).

- Interception of rainfall is expressed as function of crop coefficient K_c (-).
- Irrigation is calculated to allow α (%) of it to be lost as drainage and runoff.

Hence, Equation 1, once soil moisture reached field capacity, can be simplified in Equation 3:

Equation 3 Simplified water balance equation once soil moisture content reached field capacity.

¹ Field capacity: "the percentage of water remaining in a soil two or three days after its having been saturated and after free drainage has practically ceased" (Brady and Weil, 2001)

3.2 INPUTS, OUTPUTS AND OPERATIONS TAKEN IN ACCOUNT IN WR_MODEL

3.2.1 Model assumption

The model only considers nitrogen, phosphorus and potassium cycling from effluent to soil and tree biomass.

The time step considered is a month.

3.2.2 Model processes, inputs and outputs

On typical commercial plantations, the rotation is of 3 to 5 years duration. For this reason, in the model, a rotation cycle of 3 years is assumed and months are numbered from 1 to 36.

The different processes, inputs and outputs are summarised in Table 1.

Table 1 Model Processes, inputs and outputs ^(a)Odt : oven dry ton)

Processes	Inputs	unit
Suitability of soil for irrigation	soil conductivity, soil_EC	dS.m ⁻¹
Suitability of effluent for irrigation	soil Sodium Absorption Ratio, soil_SAR effluent conductivity, wastewater_EC effluent concentration in sodium, wastewater_[Na] effluent concentration in Calcium and Magnesium, wastewater_[Ca+Mg]	mg.L ⁻¹ dS.m ⁻¹ meq.L ⁻¹ meq.L ⁻¹
Assessment of irrigability of the field when irrigation to be started	soil moisture content at field capacity, FC soil moisture content at the beginning of irrigation, SW ₀ root zone depth, d % of irrigation accepted to drain and runoff, α	% % m %
Calculation of crop water requirement for the three years considered; average, wet and dry, for month i	Rainfall FAO reference evapotranspiration for month i, ET _{0,i}	mm.month ⁻¹ mm.month ⁻¹
Regulations compliance NVZ	FAO crop factor, K _{c,i}	(-)
Regulations compliance RB209	Interception factor	from the literature
calculation of number of years before	Local yield for tree species, η_{tree} YES/NO	odt ^(a) .ha ⁻¹ .yr ⁻¹ (-)
Calculation	sum of total N applied per ha per year initial Olsen-P. Olsen_P ₀	kg-N.ha ⁻¹ .yr ⁻¹ mg-P/kg of soil
Calculation of	Outputs	unit
Calculation of	hydrologically possible irrigation rate	mm.month ⁻¹
Calculation of	hydrologically and legally possible irrigation rate K _{irr}	mm.month ⁻¹
Calculation of	volume of biomass produced	odt.ha ⁻¹
Calculation of	minimum area to be cultivated when K _{irr} and V _{total} effluent	ha
Calculation of	volume of non-irrigable effluent	mm.month ⁻¹
Calculation of	volume of irrigation reservoir necessary to collect non-irrigable effluent	m ³

3.3 THE TECHNICAL SUB-MODEL

In this section, the step by step simulations of the model are explained. It follows the Figure 3 flow diagram.

The technical model processes are adapted from the model WATLOAD2 (Myers et al., 1999) and rearranged to comply English regulations and recommendations in term of fertilisation (RB209 (MAFF 2000), NVZ guidelines, (DEFRA, 2002a)).

The main inputs, outputs and processes of the model are described in Table 1 and the flow diagram describes the simulation steps (Figure 3).

The model is a simple dropdown, decision tree type model; i.e. calculations from one step to the next one are dependant and each step adds a greater degree of precision to the same calculation. Thus, the main steps are:

- a first irrigation rate is calculated to comply with site specific hydrological constraints
- this irrigation rate is refined and recalculated to comply also with nutrient constraints to meet regulations
- and finally this irrigation rate is refined again to assess possible Phosphorus leaching risks.

3.3.1 Model step by step description

The model is described step by step in the following paragraphs and corresponds to a detailed description of Figure 3. Numbers in parenthesis in the following paragraphs referred to the numbers in parenthesis on Figure 3.

Step (1) and (2) are general steps in order to assess the suitability of soil and effluent for irrigation:

- 1) assess the suitability of soil for irrigation (FAO, 1985); i.e. SAR and EC and Richards (Richards and Allison, 1954.) classification of soil in 4 categories, saline/alkali, saline, alkali, neither saline nor alkali.
 - If the soil is classified as either saline or alkali, then, a WaterRenew system is not recommended to be implemented on this site.
 - If the soil is not saline nor alkali, then the next step objective is to:

- 2) assess the suitability of the effluent considered for irrigation in terms of salinity which will limit plants water availability and/or infiltration rate restriction of water into soil (Westcot et al., 1985.). Their characteristics depend on effluent EC and SAR.
 - If the effluent is not complying non-salinity or sodicity characteristics, then, pre-treatment is necessary to make effluent meet a no-restriction for irrigation quality. It implies there shouldn't be a need for leaching requirement to prevent soil from salinisation.
 - If complying, then step (3) is performed:
- 3) Calculation of crop evapotranspiration during month i , ET_i using FAO Penman-Monteith equation (Allen and Food and Agriculture Organization of the United Nations., 1998.) based on $K_{c,i}$ and $ET_{0,i}$.

$$ET_i = K_{c,i} * ET_{0,i}$$

Equation 4 ET_i (mm.month⁻¹), FAO Penman-Monteith evapotranspiration for the month i , $K_{c,i}$, crop coefficient for month i (-), $ET_{0,i}$ (mm.month⁻¹), FAO Penman-Monteith reference evapotranspiration for month i , the reference is the evapotranspiration from grass.

However, as ET data can be difficult to access, a potential soil moisture deficit (PSMD) map of England and Wales is available in the model. The map was provided by extraction of soil moisture deficit data from the agroclimatic databank in the Land Information System (LandIS), of the Cranfield University National Soil Resources Institute (NSRI) by Caroline Keay and Robert Jones². England and Wales were divided in 7 agroclimatic zones identified by Robert Jones (personal communication) and reported on the map (Cf. Annex 1). Thus, the user can localise its site and enter the zone reference corresponding to its location.

- 4) Calculation of Irrigation requirements in mm.month⁻¹ to reach field capacity as function of soil water content when irrigation is started. Soil water storage is modelled as a "bucket", when.

¹ Definition from FAO 56, (Allen, 1998.): "The FAO Penman-Monteith method was developed by defining the reference crop as a hypothetical crop with an assumed height of 0.12 m, with a surface resistance of 70 s m⁻¹ and an albedo of 0.23, closely resembling the evaporation from an extensive surface of green grass of uniform height, actively growing and adequately watered."

² Jones, R.J.A. and Thomasson, A.J. (1985). An agroclimatic databank for England and Wales. Soil Survey Technical Monograph No.16, Harpenden, UK. 45 pp.

- If soil water is over field capacity, then

$$K_{irr,0} = \alpha * K_d * (SW_0 - FC) * d$$

Equation 5 $K_{irr,0}$ (mm.month⁻¹), irrigation rate for the first month of irrigation, K_d (-), drainage rate at field capacity (mm.month⁻¹), SW_0 (%), initial soil water content at the time irrigation starts, FC (%), soil water content at field capacity, d , depth of root zone (m), α , risk factor representing the % of accepted drainage and runoff of irrigated effluent out of the system without treatment ($0 \leq \alpha \leq 1$).

- If soil water is under field capacity, then:

$$K_{c,i}(ET_{0,i} + Interceptionfactor) + \alpha * K_{Irr,i} = Rainfall_i - K_{Irr,i}$$

$$K_{Irr,i} = \frac{1}{1 - \alpha} [K_{c,i}(ET_{0,i} + Interceptionfactor) - Rainfall_i]$$

with

$$\alpha * K_{Irr,i} = Runoff_i + Drainage_i$$

Equation 6 Equation of water balance with $K_{c,i}$ (-)Crop coefficient, $ET_{0,i}$ (mm/month), Interception factor of rain into foliar mass, α , risk factor representing the % of accepted drainage and runoff of irrigated effluent out of the system without treatment ($0 \leq \alpha \leq 1$).

- 5) Calculation of the amount of N applied in a year by multiplying the irrigation requirements with the nitrogen content of the effluent used for irrigation (kg.ha⁻¹.year⁻¹).
- 6) Comparison of this annual N application to N application regulation if applicable (NVZ, (GB. Parliament. Joint Committee on Statutory Instruments. et al., 1998.; GB. Parliament. Joint Committee on Statutory Instruments. et al., 2008) and RB209, (MAFF 2000). However, this amount does not guarantee there won't be any N leaching or that if occurring, N leaching is acceptable.
 - If not complying, then, recalculation of the irrigation rate to comply with it.
 - If complying, then,
- 7) Calculation of the minimum area, A_{min} (ha) necessary to cultivate to apply the monthly volume of effluent produced per month at the sustainable irrigation rate $K_{irr,i}$.

Ragg, J.M., Jones, R.J.A. and Proctor, M.E. (1988). The refinement and representation of spatial data in an information system using statistical and DBMS procedures, and trend surface analysis. Geologisches Jahrbuch. A104, 295-308. Hannover.

$$A_{\min} = \underset{i=1}{\overset{12}{\text{Max}}} \left(\frac{V_i}{K_{\text{irr},i}} \right) (\text{ha})$$

with

$$V_i = nb_i * V_{\text{total_daily_effluent},i} (\text{m}^3 \cdot \text{month}^{-1})$$

Equation 7 Calculation of the minimum area $A_{\min}(\text{ha})$ to be cultivated, $V_i (\text{m}^3 \cdot \text{month}^{-1})$, volume of effluent produced in month i , nb_i , number of days in month i , $V_{\text{total_daily_effluent},i} (\text{m}^3 \cdot \text{day}^{-1})$, the volume of effluent produced in a day during month i , $K_{\text{irr},i} (\text{mm} \cdot \text{ha}^{-1})$, sustainable irrigation rate for month i .

- 8) Calculation of the amount of phosphorus applied by irrigation ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$).
- 9) Calculation of total amount of P in soil for each month after irrigation as Olsen-P (Olsen et al., 1954.).

For month 1:

$$\text{Olsen_}P_1 = \text{Olsen_}P_0 + \alpha_{\text{Olsen_}P} * [(K_{\text{irr},1} * A_{\min} * P_{\text{Wastewater},1}) - (P_{\text{biomass},1} * \eta_{\text{plant},1})] + \beta_{\text{Olsen_}P}$$

For month $i \in \{2; 36\}$:

$$\text{Olsen_}P_i = \text{Olsen_}P_{i-1} + \alpha_{\text{Olsen_}P} * [(K_{\text{irr},i} * A_{\min} * P_{\text{Wastewater},i}) - (P_{\text{biomass},i} * \eta_{\text{plant},i})] + \beta_{\text{Olsen_}P}$$

Equation 8 Soil Olsen-P building up equation at time t with Olsen- P_0 , initial available P in soil, $P_{\text{Wastewater},j} (\text{mgP} \cdot \text{L}^{-1})$, concentration of P in wastewater at month i , the minimum area $A_{\min}(\text{ha})$ to be cultivated, $K_{\text{irr},j} (\text{mm} \cdot \text{ha}^{-1})$, sustainable irrigation rate for month i , $P_{\text{biomass},j} (\text{mgP} \cdot \text{kg}^{-1} \text{ plant})$ P content in plant at month i , $\eta_{\text{plant},i} (\text{odt} \cdot \text{ha}^{-1})$ yield of biomass at month i , $\alpha_{\text{Olsen_}P}$ $\beta_{\text{Olsen_}P}$, linear regression coefficients fitted from Cranfield data.

- 10) Comparison of the total amount of P in soil each month after irrigation to Olsen- P_{\max} ($\text{mgP} \cdot \text{kg}^{-1}$ of soil) before leaching, a soil specific value, hence total amount of P has to be smaller than Olsen- P_{\max} . Indeed, once P is applied by irrigation, it enters soil P pool and in particular, Olsen-P. Heckrath defined a maximum value of Olsen-P, Olsen- P_{\max} , for clay loam after which applied P is susceptible to leach (Heckrath et al., 1995). This Olsen- P_{\max} is soil type dependent. Moreover, the relationship between P applied by effluent and Olsen-P build up in soil has been defined in Chapter 6 for Cranfield clay as 56%. 56% of P applied by irrigation contribute to become Olsen-P. Clay P sorption capacity is greater than for other soil type (Sharpley et al., 1988); hence on using this incorporation value, the model is overestimating Olsen-P build up in soil and constraining P leaching risk.

- If not complying, then, the site is likely to leach P and therefore not suitable for a WaterRenew system to be set or its operation is not sustainable and the effluent needs to be treated before application.

- If complying, then, salinity risk has to be assessed.

11) Calculation of the amount of sodium applied by irrigation ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{month}^{-1}$).

12) Calculation of total amount of Na ($\text{meq} \cdot \text{L}^{-1}$), Ca+Mg ($\text{meq} \cdot \text{L}^{-1}$) and EC ($\text{dS} \cdot \text{m}^{-1}$) in soil for each month after irrigation.

For month 1:

$$Na_1 = Na_0 + [\alpha_{Na} * (K_{Irr,1} * A_{min} * Na_{Wastewater,1}) + \beta_{Na}]$$

For month $i \in \{2; 36\}$:

$$Na_i = Na_{i-1} + [\alpha_{Na} * (K_{Irr,i} * A_{min} * Na_{Wastewater,i}) + \beta_{Na}]$$

Equation 9 Soil Na building up equation at time i with Na_0 , initial Na in soil, $Na_{Wastewater,i}$ ($\text{mg} \cdot \text{Na} \cdot \text{L}^{-1}$), concentration of Na in wastewater, minimum area A_{min} (ha) to be cultivated, $K_{Irr,i}$ ($\text{mm} \cdot \text{ha}^{-1}$), sustainable irrigation rate for month i, α_{Na} , β_{Na} , linear regression coefficients fitted from Cranfield data.

For month 1:

$$[Ca + Mg]_1 = [Ca + Mg]_0 + [\alpha_{[Ca+Mg]} * (K_{Irr,1} * A_{min} * Na_{Wastewater,1}) + \beta_{[Ca+Mg]}]$$

For month $i \in \{2; 36\}$:

$$[Ca + Mg]_i = [Ca + Mg]_{i-1} + [\alpha_{[Ca+Mg]} * (K_{Irr,i} * A_{min} * Na_{Wastewater,i}) + \beta_{[Ca+Mg]}]$$

Equation 10 Soil Ca+Mg building up equation at time i with $Ca+Mg_0$, initial Ca+Mg in soil, $Na_{Wastewater,i}$ ($\text{mg} \cdot \text{Na} \cdot \text{L}^{-1}$), concentration of Na in wastewater, minimum area A_{min} (ha) to be cultivated, $K_{Irr,i}$ ($\text{mm} \cdot \text{ha}^{-1}$), sustainable irrigation rate for month i, $\alpha_{[Ca+Mg]}$, $\beta_{[Ca+Mg]}$, linear regression coefficients fitted from Cranfield data.

For month 1:

$$EC_1 = EC_0 + [\alpha_{EC} * (K_{Irr,1} * A_{min}) + \beta_{EC}]$$

For month $i \in \{2; 36\}$:

$$EC_i = EC_{i-1} + [\alpha_{EC} * (K_{Irr,i} * A_{min}) + \beta_{EC}]$$

Equation 11 Soil EC_i building up equation at time i with EC_0 , initial EC in soil ($\text{dS} \cdot \text{m}^{-1}$), minimum area A_{min} (ha) to be cultivated, $K_{Irr,i}$ ($\text{mm} \cdot \text{ha}^{-1}$), sustainable irrigation rate for month i, α_{EC} , β_{EC} , linear regression coefficients fitted from Cranfield data.

13) Calculation of ESP for each month:

SAR was defined as the proportion of sodium cations compared to calcium and magnesium cations.

$$SAR = \frac{[Na^+]}{\left[\frac{Ca^{2+} + Mg^{2+}}{2} \right]^{1/2}} \quad \text{Equation 12 (Richards and Allison, 1954.)}$$

ESP was defined as the “amount of exchangeable sodium expressed as a percentage of the cation exchange capacity (CEC³)” (Rowell, 1994). According to Richard (Richards and Allison, 1954.) SAR and ESP values can be linked by Equation 13:

$$ESP = \frac{100 * (0.01475SAR - 0.0126)}{1 + (0.01475SAR - 0.0126)} \quad \text{Equation 13}$$

ESP and EC were compared jointly to assess alkalinity or sodicity of a soil or water. (Richards and Allison, 1954.). There were 4 categories (Figure 2):

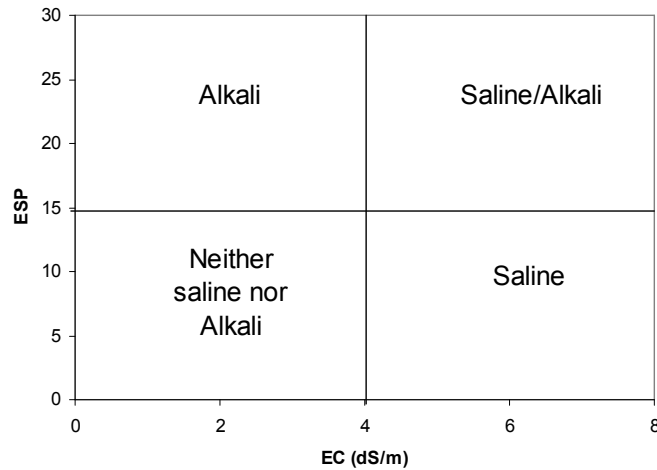


Figure 2 Soil classification according to EC and ESP. (Richards, 1954)

- If not complying, then, the site is likely to present salinisation problem and therefore not suitable for a WaterRenew system to be set or its operation is not sustainable and the effluent needs to be treated before application.
- If complying, then, the irrigation rate obtained is the sustainable irrigation rate for month i, $K_{irr,i}$ (mm.month⁻¹) for this specific site and tree species, and the minimum area to be cultivated is A_{min} (ha).

³ Cation exchange capacity or CEC: the proportion of cations “held by electrostatic forces on soil particle surfaces to balance the surface negative charge” (Rowell, 1994)

14) Calculation of volume of non-irrigable effluent produced per month, $V_{\text{effluent,non-irrigable}}$, ($\text{m}^3 \cdot \text{month}^{-1}$) defined in Equation 14. There are 3 cases when effluent cannot be irrigated; during October and February when the site is NVZ and/or when soil is already at field capacity and/or the allowed irrigation induced drainage defined by α has already been reached. This volume is stored in a pond or lagoon with a depth that is entered by the user. Therefore, an area, A_{pond} (m^2) can be calculated. But when it rains, an additional volume to $V_{\text{effluent,non-irrigable}}$ has to be taken in account. For this reason, the annual excess rainfall, XR in mm (cf. Annex 1) is accounted for the pond area calculation.

For $i \in \{1 ; 36\}$

$$V_{\text{non-irrigable effluent},i} = V_i - \text{Irrigation}_i$$

$$V_{\text{non-irrigable effluent},i+1} = V_{\text{non-irrigable effluent},i} + (V_{i+1} - \text{Irrigation}_{i+1})$$

$$\text{with } \begin{cases} V_i : \text{volume of effluent produced in month } i \text{ (m}^3\text{)} \\ \text{Irrigation}_i : \text{volume of effluent irrigated} \\ \text{during month } i \text{ (m}^3\text{)} = K_{\text{irr},i} * A_{\text{min}} \end{cases}$$

then

$$V_{\text{min}} = \text{Max}_{i=1}^{36} (V_{\text{non-irrigable effluent},i}) \text{ (m}^3\text{)}$$

$$\text{with } \begin{cases} d_{\text{pond}} : \text{depth chosen for the pond where non-irrigable effluent stored (m)} \\ A_{\text{pond}} : \text{pond / lagoon area necessary to collect } V_{\text{min}} \text{ and} \\ \text{excess rainfall, } \begin{cases} \text{XR (mm) for the location if in England or Wales} \\ \text{Rain fall - ET (mm) if not in England or Wales} \end{cases} \end{cases}$$

$$A_{\text{pond}} = \frac{V_{\text{min}} + \text{XR}}{d_{\text{pond}}} \text{ (m}^2\text{)}$$

Equation 14 Calculation of non-irrigable volume of effluent and associated necessary pond surface to store this volume.

15) Calculation of mass of wood produced per month, $M_{\text{biomass},i}$, ($\text{odt} \cdot \text{month}^{-1}$) is defined in Equation 15.

(Equation 15)

3.3.2 Model assumptions

- Leaf interception of rainfall is constant over the year.
- Rainfall, $ET_{0,i}$ and $K_{c,i}$ are uniformly distributed within the month i .
- The drainage rate $K_{d,i}$ ($\text{mm} \cdot \text{month}^{-1}$) is defined as :

$$K_{d,i} = nb_i * K_d$$

Equation 16 Definition of monthly drainage rate, $K_{d,i}$ ($\text{mm} \cdot \text{month}^{-1}$), nb_i , number of days in month i , K_d , drainage rate in $\text{mm} \cdot \text{day}^{-1}$ (from literature).

- All P applied into soil becomes plant available P and counts as Olsen-P.
- Within a year, the yield of biomass $\eta_{\text{tree}, i}$ produced is distributed by weight of relative $K_{c, i}$ on the year $K_{c, \text{year}}$.

For $i \in \{1;36\}$ (months)

and $j \in \{1;3\}$ (year in the rotation) **Equation 17**

$$\eta_{\text{tree},i} = \frac{K_{c,i}}{K_{c,j}} * \eta_{\text{tree},j}$$

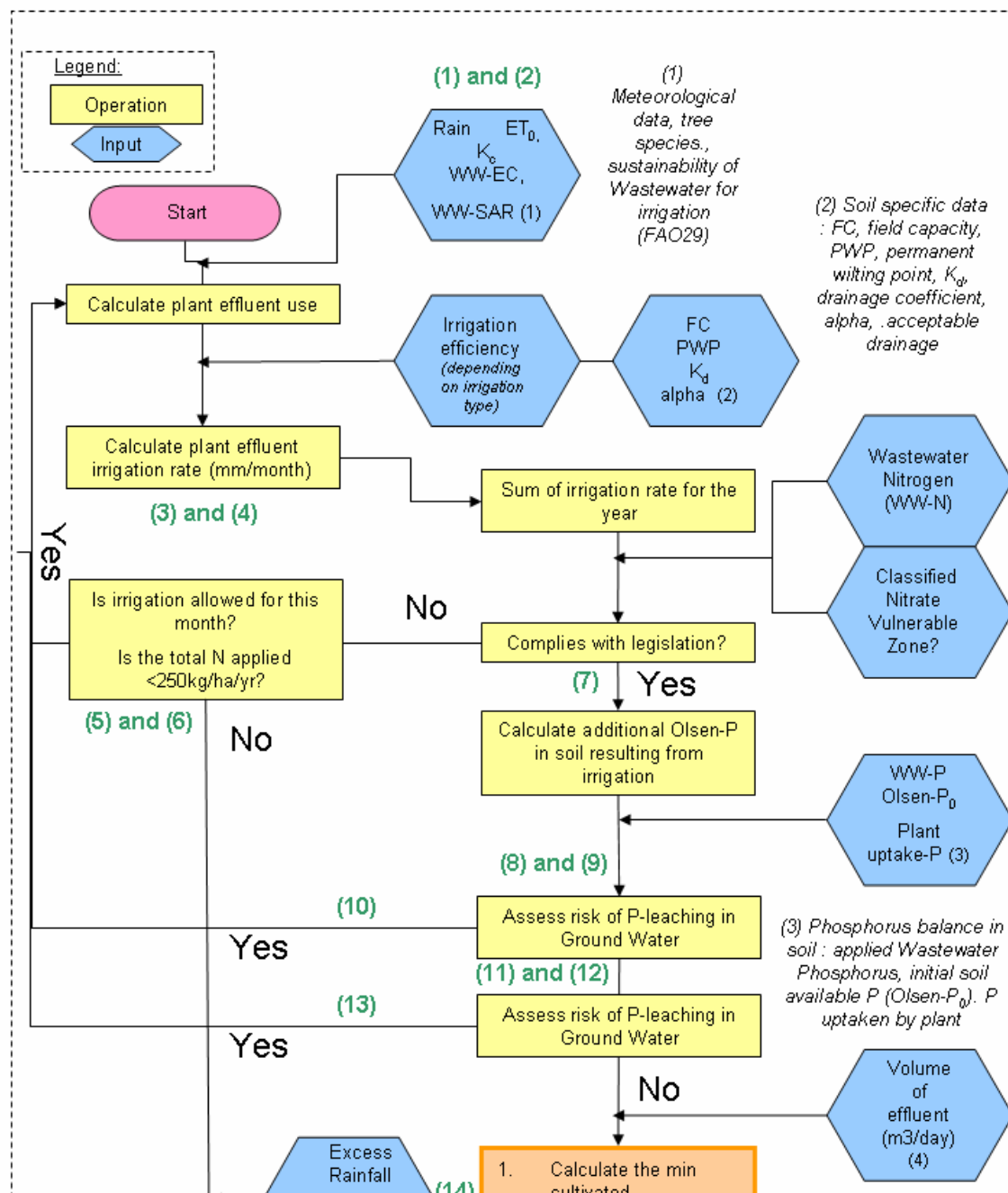


Figure 3 Flow diagram of the simulation steps in rearranged WATLOAD2. (the steps described in 4.3 are reported in green)

3.4 COST BENEFIT ANALYSIS

A conventional short rotation coppice is generally exploited for 30 years (DEFRA, 2002.a). Hence, the lifespan of a WaterRenew system will be set to 30 years.

The cost-benefit analysis at 30 years of exploitation will assess if a WaterRenew system of the area determined in part one is financially feasible. To assess this feasibility, WR_MODEL will compare prices for treating one unit of N and one unit of P by a WaterRenew System by a tertiary treatment sewage treatment plant unit. Indeed a WaterRenew system is an alternative to tertiary treatment of wastewater as one of its aim is to remove nutrients from it (DEFRA, 2002.b). Benefit from wood selling and net income will also be calculated.

The purpose of the cost benefit analysis is to help to make the decision whether or not to implement a WaterRenew system when it is technologically feasible. In other words, once the dimensioning of an environmentally sustainable system is available (Chapter 9, 3.3), is this system economically feasible?

3.4.1 Costs considered

Costs were broken down in two main categories and described in Table 2:

- 1) Capital costs
- 2) Operation and maintenance costs were calculated in total as 10 % of capital costs.

To compare the costs of treating a unit of nutrient with a WaterRenew system or with a conventional tertiary treatment, capital costs and maintenance costs were divided by 30. These calculations were simplified and cost homogeneously distributed over the 30 years period. WaterRenew system costs were calculated using one of the WaterRenew project site costs (Godinton) and data from the literature (Weatherhead et al., 2008) for reservoir/pond construction and (IGER, 2000) for other costs. To assess costs to remove N and P with a tertiary treatment plant, data from (Rosenqvist and Dawson, 2005b) were used as a reference.

Table 2 Breakdown of costs. (na ; non-applicable) for one rotation of 30 years.

Cost	WaterRenew system	Sewage plant tertiary

	<i>treatment</i>	
Construction	na	new unit
Land requirement	£.ha ⁻¹	£.ha ⁻¹
Engineering site work	site preparation, like initial plough or soil preparation + reservoir construction If clay: 1.5 £.m ⁻³ If artificially lined : 5 £.m ⁻³ (Weatherhead et al., 2008)	£.ha ⁻¹
Piping and pump	Irrigation system 4 £.m ⁻¹ pump £1100*(m ³ .h ⁻¹) ^{0.5} (IGER, 2000)	4 £.m ⁻¹ (IGER, 2000)
Subsurface consideration	advance soil analysis	£.yr ⁻¹
Operation and Maintenance cost		
Energy	Pump power, £0.03.m ⁻³ (IGER, 2000)	Pump power, £0.03.m ⁻³ (IGER, 2000)
Maintenance		
Labour		
Calculated cost of treating one unit of N	£.kgN ⁻¹	£.kgN ⁻¹ (Rosenqvist and Dawson, 2005b)
Calculated cost of treating one unit of P	£.kgP ⁻¹	£.kgP ⁻¹ (Rosenqvist and Dawson, 2005b)
SRC specific cost		
Planting cost	£.ha ⁻¹	na
Processing cost	£.ha ⁻¹	na
Transport	£.ha ⁻¹	na
Extraction	£.ha ⁻¹	na

Felling	£.ha ⁻¹	na
Return to grower	£.ha ⁻¹	na

3.4.2 Benefit considered

Benefits are established for each of the 3 alternatives considered and summarised in Table 3.

Table 3 Financial benefits engendered by implementing a WaterRenew system. (na for non applicable)

<i>Benefit</i>	<i>WaterRenew system</i>	<i>Sewage plant tertiary treatment</i>
Financial :	Timber	Sludge cake
Merchantable Product	£.ha ⁻¹	£.ha ⁻¹

However, benefits can also be social and environmental as wastewater treatment should be integrated into human water life cycle. The following criteria presented in Table 4, social and environmental would be interesting to consider and would need surveys to try to translate them into monetary values. As it was not possible to conduct those surveys during the actual projects, these criteria could be considered for further improvement of the model.

Table 4 Social and environmental benefits engendered by implementing a WaterRenew system. (na for non applicable)

<i>Benefit</i>	<i>WaterRenew system</i>	<i>Sewage plant tertiary treatment</i>
Social (not quantified numerically in the model)	Positive perception (£.ha ⁻¹) <ul style="list-style-type: none"> ○ Create a semi-natural space ○ Introduce a sustainable system ○ Protect the surroundings of the STW from noise and 	Neutral perception (£.ha ⁻¹) <ul style="list-style-type: none"> ○ as the STW is already installed, a new unit doesn't add or depreciate land value

Environmental (not quantified numerically in the model)	smell.	
	Positive impact (£.ha ⁻¹) <ul style="list-style-type: none"> ○ Production of a renewable energy source ○ Create a semi-natural space ○ Sustainable system ○ Reduce negative impact of a STW on reusing one of its potential wastes. 	Neutral impact (£.ha ⁻¹) <ul style="list-style-type: none"> ○ Treat a waste ○ Reduce natural environment

3.4.3 Financial balance, net income

The results of both Table 2 and Table 3 calculations with the minimum area to be cultivated for a sustainable WaterRenew system are balanced and their numerical results compared.

3.5 SCENARIOS COMPARED BY DEFAULT

An analysis of sensitivity of the model on different components is run automatically.

The calculation of the minimum area to be cultivated with a WaterRenew system on a specific location with a specific effluent and a specific type of trees will be automatically calculated for (cf. Figure 4 and Annex 2 section 5.1):

- Different leaching proportion allowed, i.e. within the model α equal to 5%, 10% and 50%. These leaching proportions were chosen arbitrary with an improbable upper limit of 50 %.
- With an effluent with 50% more N

Mini-Sensitivity analysis : Area necessary							
	Area to be cultivated (ha)	variation from real case (%)	Pond/lagoon surface necessary to comply NVZ rules (effluent+rainfall) (ha)	variation from real case (%)	maximum volume of effluent not treated (m³/day)	Total Area (ha)	Pond/lagoon volume necessary to comply NVZ rules (effluent+rainfall) (10³ m³)
Case 1 : 50% volume of effluent							
Average year	22.1	22%	3.2	22%	22.4	22	12
Wet year	22.1	22%	3.2	22%	22.1	22	12
Dry year	22.1	22%	3.4	22%	21.2	22	12
Case 2 : 50% more N in the effluent volume of effluent							
Average year	23.0	50%	3.1	50%	139.7	6	12
Wet year	23.0	50%	5.0	50%	25.3	61	66
Dry year	23.0	50%	1.0	50%	1-1.5	6	66

Figure 4 Output of the scenarios compared by default.

4. VERIFICATION AND SENSITIVITY ANALYSIS

4.1 VERIFICATION

According to (Jørgensen and Endorichchio, 2001)

, the verification phase can be carried out by answering 3 questions:

- 1) "Is the model stable in the long term?"

The model was designed to run 3 years at the time.

- 2) "Does the model react as expected?"

The model was tested on a data set collected on a small site, Godinton House (Kent, England) where 0.4 ha of willow were planted at a density of 18,750 tree.ha⁻¹ to treat the totality of effluent produced on site (cf. Table 5). This site was run as part of the EU-LIFE WaterRenew project by project partner WRc. The soil was classified as clay loam and the site is not on a Nitrate Vulnerable Zone (DEFRA, 2002b).

- a. soil type: clay loam

Table 5 clay loam soil physical characteristics.

	<i>PWP(%)</i>	<i>FC(%)</i>	<i>Steady infiltration rate (mm/h)</i>	<i>Hydraulic conductivity (mm/day)</i>	<i>Bulk density (g.cm⁻³)</i>
Clay Loam	21	36	3	0.27	1.32

- b. NVZ statue: NO

- c. annual PSMD⁴:

Table 6 Annual PSMD for an average year, wet year and dry year.

	<i>Average year</i>	<i>Wet year</i>	<i>Dry year</i>
Annual PSMD (mm)	694	232	1167

- d. Effluent composition:

Table 7 average effluent chemical composition at Godinton house.

	<i>Volume of effluent (L/day)</i>	<i>Nitrate (mg N/L)</i>	<i>Ammonium (mg N/L)</i>	<i>Phosphate (mg P/L)</i>	<i>Potassium (mg K/L)</i>	<i>Na (mg Na/L)</i>
Average per month	2829	75	1	9	23	84

⁴ Potential soil moisture deficit.

The model gave as answer for the area necessary to be cultivated: 0.3 ha and 0.2 to 0.4 ha of pond depending if wet, average or dry years scenarios are considered. (Figure 5)

10						
11		Area necessary				
12						
13		Area to be cultivated (ha)	Pond/lagoon superficie necessary to comply NVZ rules (effluent+rainfall) (ha)	maximum volume of effluent not treated (m ³ /day)	Total Area (ha)	Pond/lagoon volume necessary to comply NVZ rules (effluent+rainfall) (10 ³ m ³)
14	Average year	0.3	0.3	14	1	5
15	Wet year	0.3	0.4	20	1	9
16	Dry year	0.3	0.2	14	1	5

Figure 5 Outputs from WR_model for areas necessary for Godinton site.

The real site run by project partner WRc is 0.4 ha. Soil water composition was monitored at 60 cm depth during the experiment and soil water analysis did not show any contamination to its composition, hence, the model output of 0.3 ha is giving an answer in the expected range.

The model suggests also a pond area of 0.2 to 0.4 ha to store the volumes of effluent non-irrigable.

The model costs calculation is using Godinton data. They were compared with (Rosenqvist and Dawson, 2005a) costs to treat a tonne of N and a tonne of P. (Table 8):

Table 8 Costs comparison between WaterRenew and tertiary treatment unit.

	Average Cost to treat 1ton of N with WR (£)	Average Cost to treat 1ton of P with WR (£)	Average Cost to treat 1ton of K with WR (£)	Average Cost to treat 1ton of N (£) with a tertiary treatment unit ⁵	Average Cost to treat 1ton of P (£) with a tertiary treatment unit	Comparison WR and tertiary treatment unit for N (WR/tertiary)	Comparison WR and tertiary treatment unit for P (WR/tertiary)
Average year	£647,379	£4,171,999 ⁶	£1,564,500	£8,200	£13,120	79	318
Wet year	£655,246	£4,222,694	£1,583,510	£8,200	£13,120	80	322
Dry year	£645,597	£4,160,516	£1,560,194	£8,200	£13,120	79	317
	<i>Cost without pond</i>						
Average year	£4,935	£31,806	£11,927	£8,200	£13,120	0.6	2.4

⁵ (Rosenqvist and Dawson, 2005a)

⁶ The wastewater considered presents a P consent of 9 mg-P.L⁻¹, therefore, to treat a ton of P, 110 billions of effluent has to be treated. In this particular case, it will take 107 years before treating one ton of P.

Wet year	£4,935	£31,806	£11,927	£8,200	£13,120	0.6	2.4
Dry year	£4,935	£31,806	£11,927	£8,200	£13,120	0.6	2.4

With the pond and lagoon, WR costs to treat a tonne of N were over 79-fold greater than tertiary treatment and over 310-fold greater for P. However, on Godinton site, all effluent produced on site was irrigated on the 0.4 ha without having any negative effect on soil water composition. Therefore, WR costs without the costs of pond constructions were also considered. In that case, WR costs to treat a tonne of N were 60 % of the ones from tertiary treatment plots and over 2.4-fold greater for P.

3) Are all the applied units checked and verified?

All the units for all the parameters and variables were successfully checked.

4.2 SENSITIVITY ANALYSIS

4.2.1 Definition and selection of parameters and variables

(Jørgensen and Endoricchio, 2001)

described the “sensitivity analysis” as the step in modelling that “attempts to provide a measure of the sensitivity of either parameters or forcing functions, or sub-models to the state variables of greatest interest in the model.”

Therefore (Jørgensen and Endoricchio, 2001)

defined sensitivity, S , of a parameter, P as follow for x is the state variable considered:

$$S = \frac{\left[\frac{\partial x}{\partial P} / x \right]}{\left[\frac{\partial P}{\partial P} / P \right]} \quad \text{Equation 18}$$

For WR_MODEL, the main parameters considered for sensitivity analysis are:

- Soil types: 5 levels clay, loam clay, loam, sandy loam, sand.
- Tree: 3 levels willow, poplar, eucalyptus.
- NVZ : 2 levels YES, NO
- Climate: 7 levels of annual PSMD (mm) for the main agroclimatic zones for England, Wales and Scotland.

The state variables considered were:

- Area to be cultivated (ha)
- Pond/lagoon area necessary to comply NVZ rules (effluent +rainfall) (ha)

4.2.2 Results on example data set (Godinton) on the sensitivity analysis

The reference chosen to run the sensitivity analysis was Godinton House (Kent, England) site data.

- The variations of soil type and tree parameters did not engender any variation in area to be cultivated, nor pond area, nor total area. Hence, cultivated and pond areas were not sensitive to soil types and tree species.
- NVZ and climate did change all the areas and sensitivity calculations are presented in Table 9.

Table 9 Sensitivities table for PSMD variations on area cultivated and pond area (cf. map in Annex 1 where zones represent England and Wales climatic zones, cf. Userguide Section 4.2).

		zone 1	zone 2	zone 3	zone 5	zone 6	zone 7
Average year	$S_{\text{cultivated}}$	-2.2	-1.9	37.3	0.9	5.8	-4.4
	S_{pond}	-1.8	-2.7	-1.7	-2.9	2.1	-1.8
Wet year	$S_{\text{cultivated}}$	-3.1	-2.5	81.8	2.6	8.5	-5.7
	S_{pond}	-0.2	-0.2	-0.2	-3.7	0.2	-0.2
Dry year	$S_{\text{cultivated}}$	-1.9	-1.6	24.9	0.6	5.0	-4.1
	S_{pond}	-2.4	-5.4	-3.4	-1.9	3.2	-2.1

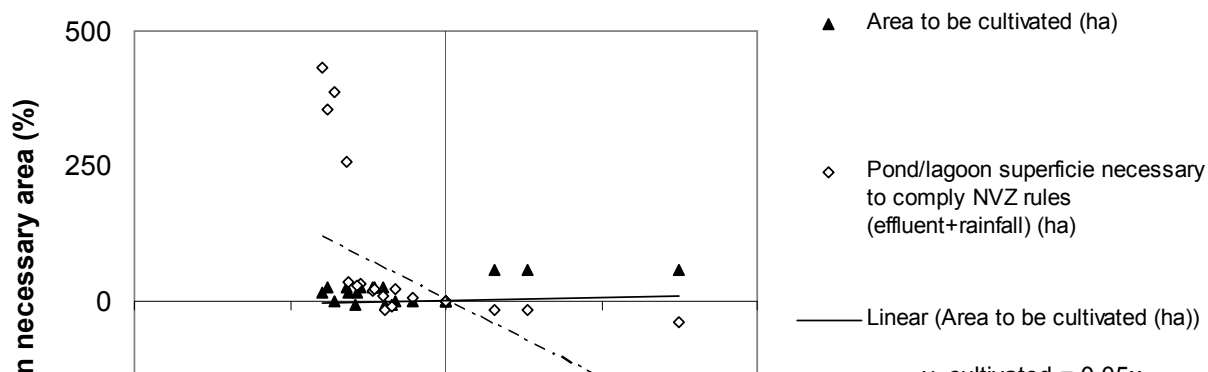


Figure 6 Sensitivity, S calculation for varying PSMD (mm) on area cultivated and area needed for lagoon.

Linear regressions were performed to determine sensitivities, S , for PSMD variations.

As $S_{\text{cultivated}}=0.05$ (cf. Figure 5) was positive, positive variations of PSMD engendered positive variations of area cultivated; i.e. when the amount of effluent hydrologically irrigable was greater, then the area to be cultivated resulted greater.

As $S_{\text{pond}}=-1.46$ (cf. Figure 5), positive variations of PSMD engendered negative variations of pond/lagoon area to stock non-irrigable effluent; i.e. when greater amount irrigable, then the pond area resulted smaller.

However, for both area, coefficients of determination were very low ($-0.61 < 0$ and $0 < 0.15$). Therefore, area to be cultivated appeared to be relatively not sensitive to PSMD variation, whereas pond surface appeared to be. As cultivated area depends also on soil properties (even though not sensitively), it could explain the lower sensitivity of the cultivated area. However, pond surface depends only on climatic data and this explains its greater sensitivity to PSMD variations.

Therefore, the model appears as being mostly sensitive to climatic conditions. This is in accordance with the way the model was built; constrained mainly by hydrological properties of the system. It is surprising that the model was not sensitive to soil types as infiltration rate and water holding properties are also hydrological properties of the system. This could not be explained by a greater range of variations between climatic factors (amplitude of PSMD variation ranged from 86 % to 250 % of the average of all data) and soil physical factors (amplitude of hydraulic soil properties' variation ranged from 75 % to 250 %).

For NVZ:

Table 10 Sensitivities table for varying NVZ statue on cultivated area and pond area.

<i>Rain</i>	$S_{\text{cultivated}}$	S_{pond}
Average year	34.0	-8.3
Wet year	34.0	-9.0
Dry year	34.0	-10.8

As NVZ statute is a qualitative parameter, variation of the parameter was equalled to 1. As there are only 2 levels for NVZ statue parameter, it was not possible to conduct a linear regression. Therefore it is difficult to assess area to cultivate and pond area to NVZ statue. (If a site is NVZ, it means the annual N load has to be limited to 250 kg-N.ha⁻¹.year⁻¹.)

5. CONCLUSION

The specific objectives of this chapter were to:

- **Objective 1:** present, describe and explain this design and decision making tool for a WaterRenew system, WR_MODEL. WR_MODEL is a tool to dimension a sustainable WaterRenew system on a specific site, with a specific effluent, and a specific tree species. It also assesses its financial viability compared to a wastewater tertiary treatment unit on a sewage treatment work to remove nutrients. WR_MODEL was designed to be used in the UK as default data on soil and climate are UK specific. Calculations are also constrained to comply UK specific recommendations in terms of fertilisation.
- **Objective 2:** verify (there were not enough data to validate the model) on running Godinton (Kent, UK) set of data and conduct a sensitivity analysis to identify the sensitivity of the models to its parameters. The model appeared to be very sensitive to climatic conditions and not so much to soil type. This is in accordance with the way the model was built; constrained mainly by hydrological properties of the system.

The model was built using parameters determined by the Cranfield University field trial. Even though it has been verified and a partial sensitivity analysis performed, the model has not been validated as there was no independent, complete data set available. Therefore, the model greatest weakness lies in the fact all accumulations of different nutrients (P, K, Na, SAR and EC) in soil were determined on Cranfield site field trial. This trial was limited in time (2 years) and in space (22 m by 22 m). Therefore, determining the nutrients accumulations for different types of soil will be effectively the next step in terms of adding confidence in WR_MODEL outputs.

6. REFERENCES

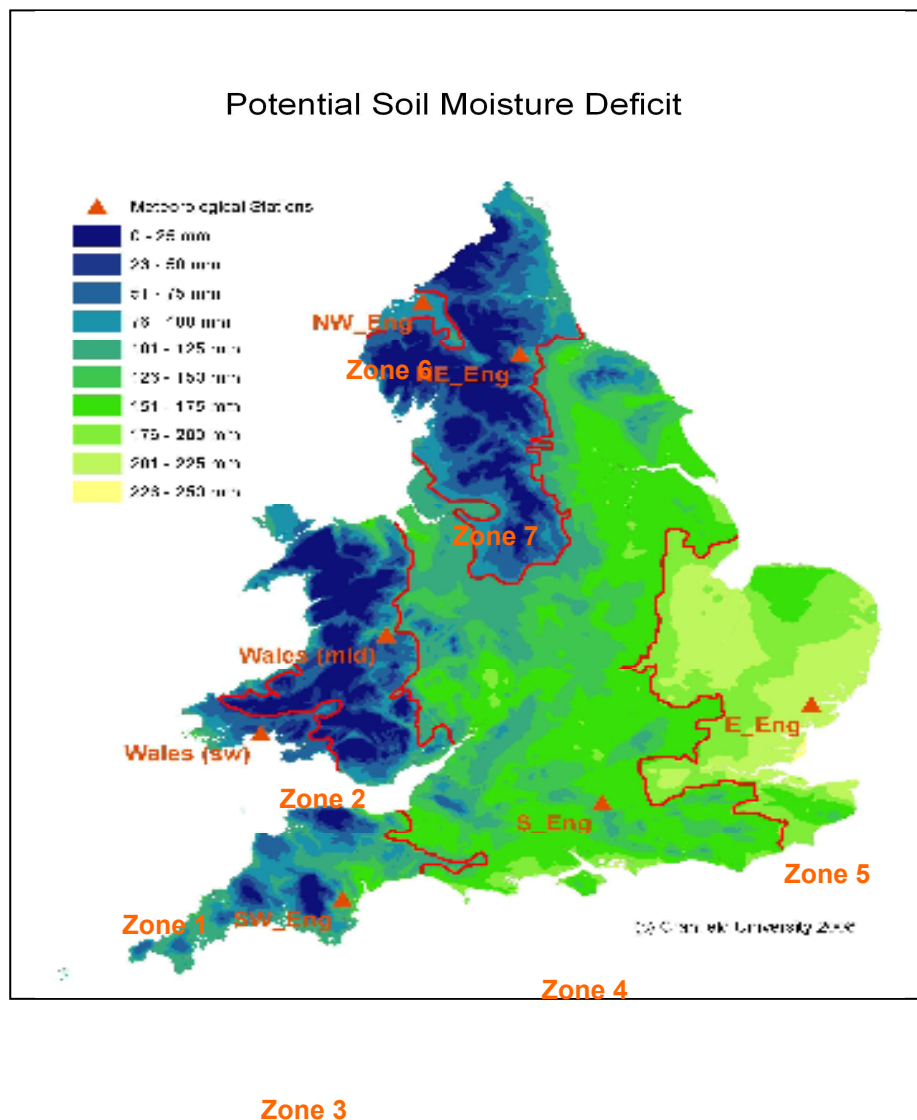
- Allen, R. G. (. G.). and Food and Agriculture Organization of the United Nations. (1998.), *Crop evapotranspiration : guidelines for computing crop water requirements*, Food and Agriculture Organization of the United Nations, Rome.
- Aronsson, P. G., Bergstrom, L. F. and Elowson, S. N. E. (2000/2), "Long-term influence of intensively cultured short-rotation Willow Coppice on nitrogen concentrations in groundwater", *Journal of Environmental Management*, vol. 58, no. 2, pp. 135-145.
- Brady, N. C. and Weil, R. R. (eds.) (2001), *The Nature and Properties of Soils*. Prentice Hall, New York.

- DEFRA (2002.a), *Growing short rotation coppice : best practice guidelines for applicants to DEFRA's energy crops scheme*. DEFRA, London.
- DEFRA (2002.b), *Sewage treatment in the UK : UK implementation of the EC Urban Waste Water Treatment Directive : sensitive areas : September 2002*, Department for Environment, Food & Rural Affairs, London.
- DEFRA (2002a), "Guidelines for Farmers in NVZs – England.", vol. PB5505.
- DEFRA (2002b), *Implementation of the Nitrates Directive (91/676/EEC), Description of the methodology applied by the Secretary of State in identifying additional Nitrate Vulnerable Zones in England*. Water Quality Division, 1.
- Heckrath, G., Brookes, P. C., Poulton, P. R. and Goulding, K. W. T. (1995), "Phosphorus Leaching from Soils Containing Different Phosphorus Concentrations in the Broadbalk Experiment", *Journal of Environmental Quality*, vol. 24, no. 5, pp. 904-910.
- IGER (2000), "Soil based treatment systems for dirty water", *-Final Project Report -*, .
- Jørgensen, S. E. and Endorichio, G. (2001), "Fundamentals of ecological modelling. 3rd edition", vol. 21, pp. 1-530.
- MAFF, (2000), *Fertiliser recommendation for agricultural and horticultural crops (RB209)*, Seventh edition ed., the stationary office, London, UK.
- Myers, B. J., Bond, W. J., Benyon, R. G., Falkiner, R. A., Polglase, P. J., Smith, P. J., Snow , V. O. and Theiveyanathan, S. (1999), "Sustainable Effluent-Irrigated Plantations: An Australian Guideline", *CSIRO Forestry and Forest Products*, .
- Richards, L. A. and Allison, L. E. (1954.), *Diagnosis and improvement of saline and alkali soils*, U.S. Government Printing Office, Washington, D.C.
- Rosenqvist, H. and Dawson, M. (2005a), "Economics of using wastewater irrigation of willow in Northern Ireland", *Biomass and Bioenergy*, vol. 29, no. 2, pp. 83-92.
- Rosenqvist, H. and Dawson, M. (2005b), "Economics of using wastewater irrigation of willow in Northern Ireland", *Biomass and Bioenergy*, vol. 29, no. 2, pp. 83-92.
- Rowell, D. L. (1994), *Soil science : methods and applications*, Longman Scientific & Technical, Harlow.
- Sharpley, A. N., Curtin, D. and Syers, J. K. (1988), "Changes in Water-extractability of Soil Inorganic Phosphate Induced by Sodium Saturation", *Soil Science Society of America Journal*, vol. 52, no. 3, pp. 637-640.
- Weatherhead , K., Knox, J. and Kay, M. (2008), "Thinking about an irrigation reservoir? - a guide to planning, designing, constructing and commissioning a water storage reservoir-", .
- Westcot, D. W. (1988), "Reuse and disposal of higher salinity subsurface drainage water — A review", *Agricultural Water Management*, vol. 14, no. 1-4, pp. 483-511.
- Westcot, D. W., Food and Agriculture Organization of the United Nations. and Ayers, R. S. (1985.), *Water quality for agriculture*, Food and Agriculture Organization of the United Nations, Rome.

7. APPENDICES

7.1 APPENDICE 1: MAP OF ENGLAND AND WALES CLIMATIC ZONES

The map was provided by extraction of soil moisture deficit data from the agroclimatic databank in the Land Information System (LandIS), of the Cranfield University National Soil Resources Institute (NSRI) by Caroline Keay and Robert Jones⁷.



⁷ Jones, R.J.A. and Thomasson, A.J. (1985). An agroclimatic databank for England and Wales. Soil Survey Technical Monograph No.16, Harpenden, UK. 45 pp.

Ragg, J.M., Jones, R.J.A. and Proctor, M.E. (1988). The refinement and representation of spatial data in an information system using statistical and DBMS procedures, and trend surface analysis. Geologisches Jahrbuch. A104, 295-308. Hannover.

7.2 APPENDICE 2: WR_MODEL USERGUIDE: WATERRENEW MODEL USER GUIDE

1. INTRODUCTION

A WaterRenew system is a system where wastewater polishing is coupled with fast growing wood crops production. It comprises soil profile from surface to the root depth d (m), soil water contained in this soil profile and the vegetation growing at the surface of this soil profile.

The beneficial advantages of such a system are environmental, social and economical at the condition that it works safely.

Hence, the main concern on implementing a WaterRenew system as a complement to wastewater treatment is the environmental risk associated with irrigation with treated effluent. More precisely, the risk of contamination of any of the compartments acting in a WaterRenew system, i.e. soil and soil water (as vegetation is exported from the system, its possible contamination is less critical):

- Damage on soil water: Soil water's changes can be environmentally damageable as soil water is vector of its solutes to groundwater and/or surface waters.
- Damage on soil: The soil could be damage in terms of its structure, texture, dis-equilibrated nutrient content and suffers salinisation.

This technology is not new, it is on commercial use in Australia (Myers et al., 1999), Sweden (Aronsson et al., 2000/2) and the USA (Paranychianakis et al., 2006). However, this system is very site-dependant because it relies heavily on meteorological and soil properties for evapotranspiration as any production system involving plants (Allen and Food and Agriculture Organization of the United Nations., 1998.) Hence, the design of a WaterRenew system is very site specific and can be assisted by a tool. There are some existing model like WATLOAD2 to dimension an effluent irrigated Eucalyptus plantation under Australian edapho-meteorological conditions and WATCOST to assess economical benefit from such a plantation, both developed by Myers et al (Myers et al., 1999). However WATLOAD2 cannot be directly used in the UK for two reasons:

- first, WATLOAD2 is calibrated for Australian biometeorological zones

- second, neither EU nor British regulations are taken in account to calculate the minimum area to cultivate to set a sustainable system.

For this reason, WR_MODEL was developed, following processes described in WATLOAD2 and completed with a cost benefit tool.

Indeed, WR_MODEL does two different things:

- 1) It calculates the minimum area necessary to cultivate as a WaterRenew system and pond capacity to treat the totality of wastewater produced at a sewage treatment work on a specific site under specific meteorological and edaphic conditions.
- 2) It calculates the cost of installing the WaterRenew system and pond characterised in 1), benefit engendered by biomass production and then compares the resulting cost-benefit to the cost of treating the same volume of wastewater with conventional nutrient removal methods (chemically or biologically).

This guide will present how to use the model step by step and is presenting also a Layman guide at the end to give a general feeling (overview) of the modelling philosophy followed.

A main hypothesis of the model is that on applying effluent to a rate to keep soil moisture under or as a maximum to field capacity, drainage of soil water to deeper layers of soil and eventually groundwater is consequently very limited and can be considered as not significant.

A built in library with trees, soil type's characteristics allow users without site specific information to run the model. However, meteorological information as effluent characteristics are indispensable.

2. DISCLAIMER

This model outputs are recommendations for the area to be considered to implement a WaterRenew system and those recommendations need to be validated by a FACTS (Fertiliser Advisers Certification and Training Scheme) certified body.

3. MODEL GENERAL DESCRIPTION

WR_MODEL is an excel spreadsheet regrouping 8 interdependent worksheets.

Physical (water movement in and out soil compartment) and chemical (nutrients and sodium interactions between soil, soil water and plants) processes were separated and looked at in different worksheet.

The aim of each worksheet is to adjust, by taking into account the specific process, the minimum area necessary to cultivate to treat the totality of treated wastewater produced on a specific plant and complying with the specific regulations and guidelines for each element.


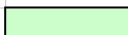
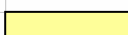

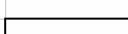
Below are described each of the 8 worksheet constituting the model:

- **“Start”**: Input worksheet where all site specific information has to be entered. The following data are necessary: Climate and hydrological data, soil hydraulic characterisation, soil nutrient characterisation, tree species to be used and effluent production volume and chemical characterisation.
- **“1_Hydrology”**: calculates hydrologically possible irrigation rate (mm/ha) in order to minimize surface runoff and drainage.
- **“2_Nutrient_N”**: calculates firstly a initial minimum area to cultivate based on the previously defined irrigation rate (if less than 0.5mm/day, irrigation rate is considered as 0) and effluent characteristics (production rate and chemical composition, in particular Nitrogen). This initial minimum area is readjusted to calculate the actual minimum cultivation area and additional storage capacity to comply Nitrogen application regulation (RB 209, NVZ)
- **“3_Nutrient_P”**: calculates the life expectancy of the site by using the actual minimum cultivation area and Phosphorus application recommendation (RB209). Soil has a limited sorption capacity and the filling-up of this limited sorption capacity is modelled as a linear function of P applied.
- **“4_Nutrient_K”**: calculates Potassium balance by using the actual minimum cultivation area and K application recommendation (RB209).
- **“5_Nutrient_Na”**: assesses soil salinisation risks by using the actual minimum cultivation area, soil saline statue (Sodium Absorption Ratio, SAR and Electrical Conductivity, EC) and Na application recommendation (FAO 55, FAO29).
- **“6_Cost”**: calculates Costs-benefit balance.

- **“Conclusion”**: presents results of simulation, in particular, the minimum area to cultivate, the additional storage for non-irrigable effluent, Cost-benefit balance and indication on the sustainability of the system with the time necessary to fill soil P sorption capacity and on salinisation risks.
- **“7_Appendix”** : it is a built in library storing generic tree and soil type characteristics to allow users with very limited site specific knowledge to run simulations if meteorological data are available.
- **“Glossary”** : a glossary with definitions of technical and general terms used in the model.

4. RUNNING SIMULATIONS

- Double click on **WR_model.xls** to start a simulation and fill the **“Start”** worksheet.
- There is a general colour code:

	COLOUR CODE							
		: input data entered by user						
		: constant data part of the built in library (values from the literature)						
		: imported data from previous calculation from other spreadsheet						
		: calculated values						
		: intermediate calculated values						
•								

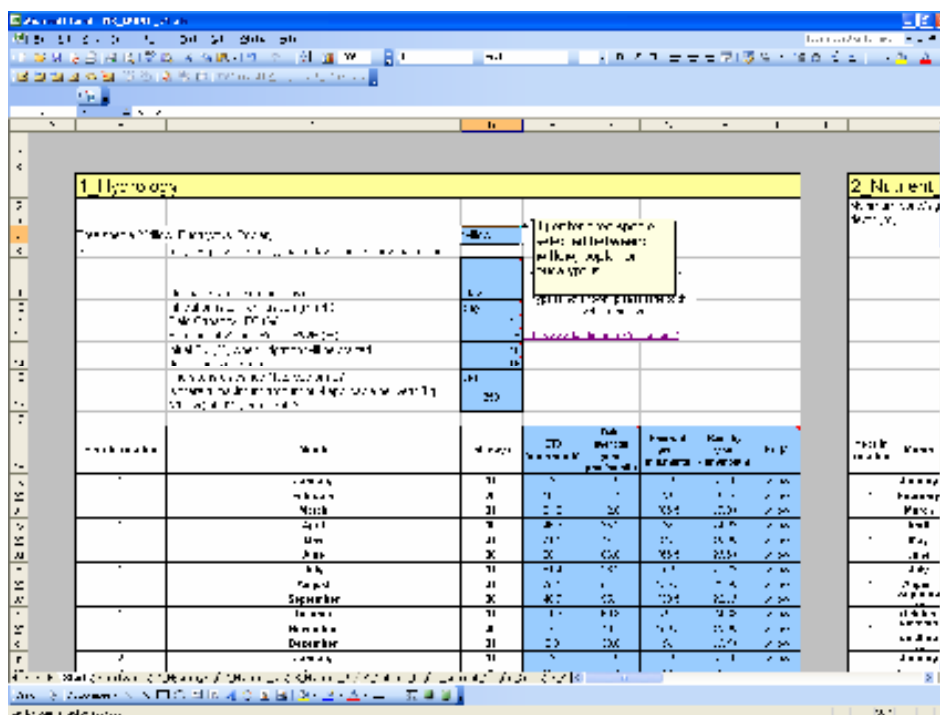
4.1 WORKSHEET START

This worksheet is divided in 5 sections.

Each section corresponds to the entry data section of the following worksheets.

4.2 HYDROLOGICAL SECTION (1_HYDROLOGY) OF THE START WORKSHEET

1. Enter tree specie selected between willow, poplar and eucalyptus.
2. Enter the soil type of your site in cell D8.



3. Enter site soil characteristics: if not known for the particular site, then by entering soil type (among 5 types, clay, loam clay, loam, sandy loam, sand) the model generates the necessary values from the literature for the soil type in question. If soil type of the location is not known, then the following link will provide information to decide which soil type to consider.
<http://www.landis.org.uk/soilscapes/>

For each parameter, enter soil type or real values from cell D9 to D12.

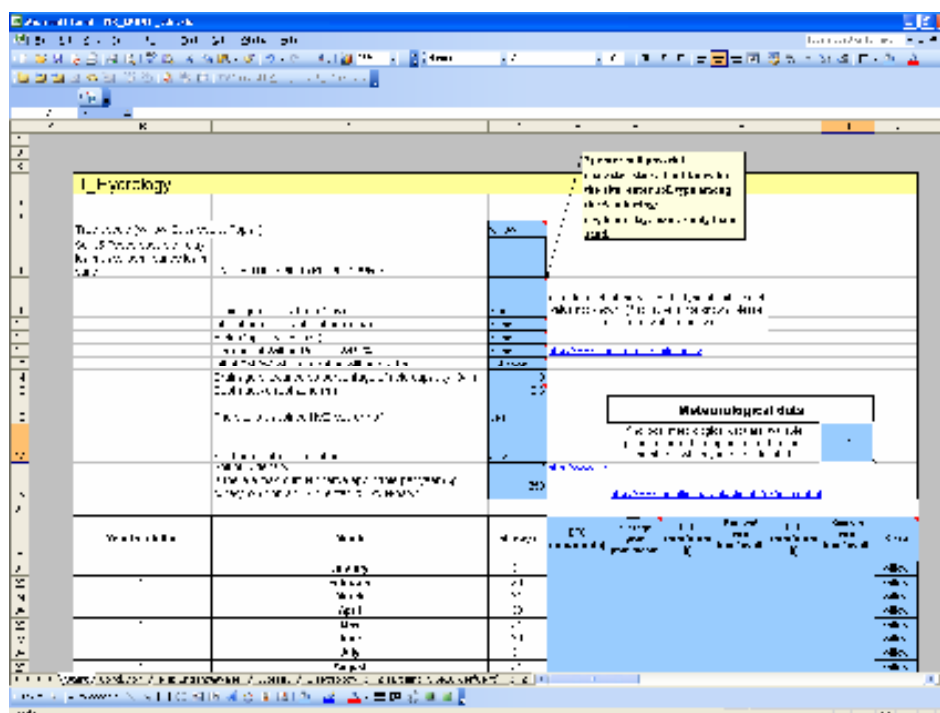
4. Enter initial soil moisture content (%) in cell **D13**. However, if not known, enter « unknown » and a default value of 90% of the field capacity value will be entered for calculation. Because the application amount of effluent is soil moisture dependent, irrigable amount is calculated to bring soil moisture to a maximum of field capacity, hence, a “bad” condition starting point it considered by default.

The screenshot shows a spreadsheet with several sections. Section 1, titled 'Hydrology', contains input fields for parameters like 'Evaporation coefficient', 'Root zone depth', and 'Crop coefficient'. Section 2, titled 'Climate', contains input fields for 'Rainfall' and 'Temperature'. A table at the bottom lists monthly data for a 36-month period, including rainfall, evaporation, and crop coefficient values.

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Rainfall (mm)	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350	360
Evaporation (mm)	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350	360
Crop coefficient	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

- Irrigation induced drainage can be permitted. This proportion can be chosen and entered in cell **D14**.
- Enter the depth of active root zone in cell **D15**. However, if not known, as for the tree species considered, willow, poplar and eucalyptus, the maximum root density zone is around 0.3 m and on entering "unknown" the model will consider automatically 0.6 m as active root zone depth.
- Enter "Yes" if site in (Nitrate Vulnerable Zone) NVZ or "No" in cell **D16**.
- Enter FAO reference evapotranspiration data (cells **E22- E57**, cells **G22- G57**, cells **I22- I57**). (NB. ET are not likely to change too much between a wet and dry year so if only one set was available, it could be used for the 3 years, average, wet and dry, (Robert Jones, personal communication)). Then enter rainfall (mm/month) for a period of 36 month first for an average year (cells **F22-F57**), then rainfall for a wet year(cells **H22-H57**), and finally, rainfall for a dry year (cells **J22-J57**), and Kc (monthly crop coefficient value) or tree species if no data available for the 36 month (cells **K22- K57**). As the model is highly hydrologically driven, in particular, rainfall data are very important. Wet and dry years do happen and can't be predicted but nevertheless need to be taken in account.

As evapotranspiration data can be difficult to access, a map is available on worksheet **Map England & Wales**. The map was put on by Caroline Keay for by extracting the moisture deficit data from the agroclimatic databank⁸ in the Land Information System (LandIS), of the Cranfield University National Soil Resources Institute (NSRI). Hence, the zone number corresponding to the location of the site can be entered in cell **J17**.



4.3 WASTEWATER SECTION (2_NUTRIENT_N) OF THE START WORKSHEET

1. Enter pond or wastewater lagoon depth commonly in use in the location (m) in cell **O6**.
2. Enter wastewater data: daily volume of effluent produced, average composition (monthly if available or average) from cell **P22-P57** to **U22-U57**.

⁸ JONES, R.J.A. and THOMASSON, A.J. (1985). An agroclimatic databank for England and Wales. Soil Survey Technical Monograph No.16, Harpenden, UK. 45 pp.

RAGG, J.M., JONES, R.J.A. and PROCTOR, M.E. (1988). The refinement and representation of spatial data in an information system using statistical and DBMS procedures, and trend surface analysis. *Geologisches Jahrbuch*. A104, 295-308. Hannover.

Year	Month	Day	Volume of water (m³/ha)	Mass of P (kg/ha)	Mass of N (kg/ha)	% of P in the water
2000	Jan	1	1.8	1.8	1.8	1.8
2000	Jan	2	1.8	1.8	1.8	1.8
2000	Jan	3	1.8	1.8	1.8	1.8
2000	Jan	4	1.8	1.8	1.8	1.8
2000	Jan	5	1.8	1.8	1.8	1.8
2000	Jan	6	1.8	1.8	1.8	1.8
2000	Jan	7	1.8	1.8	1.8	1.8
2000	Jan	8	1.8	1.8	1.8	1.8
2000	Jan	9	1.8	1.8	1.8	1.8
2000	Jan	10	1.8	1.8	1.8	1.8
2000	Jan	11	1.8	1.8	1.8	1.8
2000	Jan	12	1.8	1.8	1.8	1.8
2000	Jan	13	1.8	1.8	1.8	1.8
2000	Jan	14	1.8	1.8	1.8	1.8
2000	Jan	15	1.8	1.8	1.8	1.8
2000	Jan	16	1.8	1.8	1.8	1.8
2000	Jan	17	1.8	1.8	1.8	1.8
2000	Jan	18	1.8	1.8	1.8	1.8
2000	Jan	19	1.8	1.8	1.8	1.8
2000	Jan	20	1.8	1.8	1.8	1.8
2000	Jan	21	1.8	1.8	1.8	1.8
2000	Jan	22	1.8	1.8	1.8	1.8
2000	Jan	23	1.8	1.8	1.8	1.8
2000	Jan	24	1.8	1.8	1.8	1.8
2000	Jan	25	1.8	1.8	1.8	1.8
2000	Jan	26	1.8	1.8	1.8	1.8
2000	Jan	27	1.8	1.8	1.8	1.8
2000	Jan	28	1.8	1.8	1.8	1.8
2000	Jan	29	1.8	1.8	1.8	1.8
2000	Jan	30	1.8	1.8	1.8	1.8
2000	Jan	31	1.8	1.8	1.8	1.8

4.4 PLANT UPTAKE AND NUTRIENT BALANCE SECTION (3_NUTRIENT_P) OF THE START WORKSHEET

1. Enter planting density of the SRC in cell D62 (the literature reports planting density ranging from 10,000 to 30,000 trees/ha) (Great Britain. Dept. for Environment, Food & Rural Affairs, 2002.)

Year	Month	Day	Volume of water (m³/ha)	Mass of P (kg/ha)	Mass of N (kg/ha)	% of P in the water
2000	Jan	1	1.8	1.8	1.8	1.8
2000	Jan	2	1.8	1.8	1.8	1.8
2000	Jan	3	1.8	1.8	1.8	1.8
2000	Jan	4	1.8	1.8	1.8	1.8
2000	Jan	5	1.8	1.8	1.8	1.8
2000	Jan	6	1.8	1.8	1.8	1.8
2000	Jan	7	1.8	1.8	1.8	1.8
2000	Jan	8	1.8	1.8	1.8	1.8
2000	Jan	9	1.8	1.8	1.8	1.8
2000	Jan	10	1.8	1.8	1.8	1.8
2000	Jan	11	1.8	1.8	1.8	1.8
2000	Jan	12	1.8	1.8	1.8	1.8
2000	Jan	13	1.8	1.8	1.8	1.8
2000	Jan	14	1.8	1.8	1.8	1.8
2000	Jan	15	1.8	1.8	1.8	1.8
2000	Jan	16	1.8	1.8	1.8	1.8
2000	Jan	17	1.8	1.8	1.8	1.8
2000	Jan	18	1.8	1.8	1.8	1.8
2000	Jan	19	1.8	1.8	1.8	1.8
2000	Jan	20	1.8	1.8	1.8	1.8
2000	Jan	21	1.8	1.8	1.8	1.8
2000	Jan	22	1.8	1.8	1.8	1.8
2000	Jan	23	1.8	1.8	1.8	1.8
2000	Jan	24	1.8	1.8	1.8	1.8
2000	Jan	25	1.8	1.8	1.8	1.8
2000	Jan	26	1.8	1.8	1.8	1.8
2000	Jan	27	1.8	1.8	1.8	1.8
2000	Jan	28	1.8	1.8	1.8	1.8
2000	Jan	29	1.8	1.8	1.8	1.8
2000	Jan	30	1.8	1.8	1.8	1.8
2000	Jan	31	1.8	1.8	1.8	1.8

2. Enter soil P data, there are 3 possibilities, enter either 1) Olsen-P in mg/L in cell **D64** (unit of RB209, Appendix 4), or 2) RB209 Appendix 4 P index, in cell **D66** or 3) Olsen-P in mg/kg of soil in cell **D68**. Only one value is necessary, however, 3 entries are necessary (enter “unknown” if no value).

	A	B	C	D	E	F	G
54			December	0.1	0.2	0.3	0.4
55							
56							
57							
58			Plant density (broccoli)		15000		
59			Soil NPK		0.05		
60			Soil P index 1		0		
61			Olsen-P (mg/L)		0		
62			Calcium (mg/kg)		0		
63			Index P (Olsen P as defined by Appendix 4 up to 1671)		0		
64			Index K (Olsen P as defined by Appendix 4 up to 1671)		0		
65			Chlorophyll content		24		
66			Start of irrigation		September		
67			Depth of irrigation		1.50		
68			Bulk density (g/cm³)		1.32		
69							
70							
71							
72							
73							
74							
75							
76							
77							
78							
79							
80							
81							
82							
83							
84							
85							
86							
87							
88							
89							
90							
91							
92							
93							
94							
95							
96							
97							
98							
99							
100							

4.5 SALINISATION SECTION (5_NUTRIENT_NA) OF THE START WORKSHEET

if available enter the following data for soil SAR assessment from soil saturated paste extract: Na in cell **P62**, Ca+Mg concentrations in cell **P63** and EC (dS/m) in cell **P64** (Richards, 1954).

[illegible]

4.6 COST SECTION (6_COST) OF THE START WORKSHEET

1. Enter land price for the location around the sewage treatment work in cell **D76** and the actual value of saleable biomass in cell **D77**. However, if this value is not known, enter tree specie in cell **D77** and a 2008 average value can be withdrawn by the model.
2. To take in account eventual transport costs, enter in cell **D78** the distance between the plant and the field where a WaterRenew system is to be implemented.

(If transport is needed, it will be done by pipes and effluent pumped into the system).

The input worksheet is finally filled-in and results are presented in worksheet Conclusion.

5.1 RESULTS TABLES

9-44

3 tables are produced presenting for each of the rainfall regime (average, wet or dry).

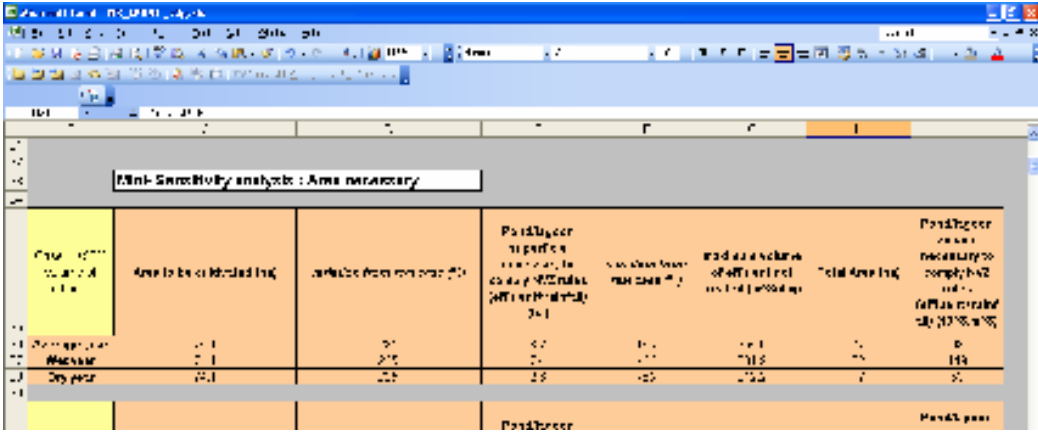
The first table present the area necessary to plant with trees, the minimum area or volume necessary to build as an irrigation reservoir.

The second one presents the 30 years cost-benefit balance with the initial investment necessary to implement a WaterRenew system, then the benefits of selling wood after 3 years, the net income over 30 years and the average cost to treat a ton of N, P and K with a WaterRenew system. The average costs of treating a ton of N and P with a conventional tertiary treatment unit are also reported (Rosenqvist and Dawson, 2005).

The third table presents an indication about the sustainability of the WaterRenew system implemented on considering how fast soil Phosphorus sorption capacity might be filled, then if there is a risk of salinisation. (These information are guidelines as modelling of these processes is based only on one specific site ran for 3 years only).

Then, a basic sensitivity analysis is performed to give an idea on how big the system should be for two cases:

- 1) if there was 50% more effluent (in terms of volume)
- 2) if with the same volume of effluent, it was containing 50% more N.

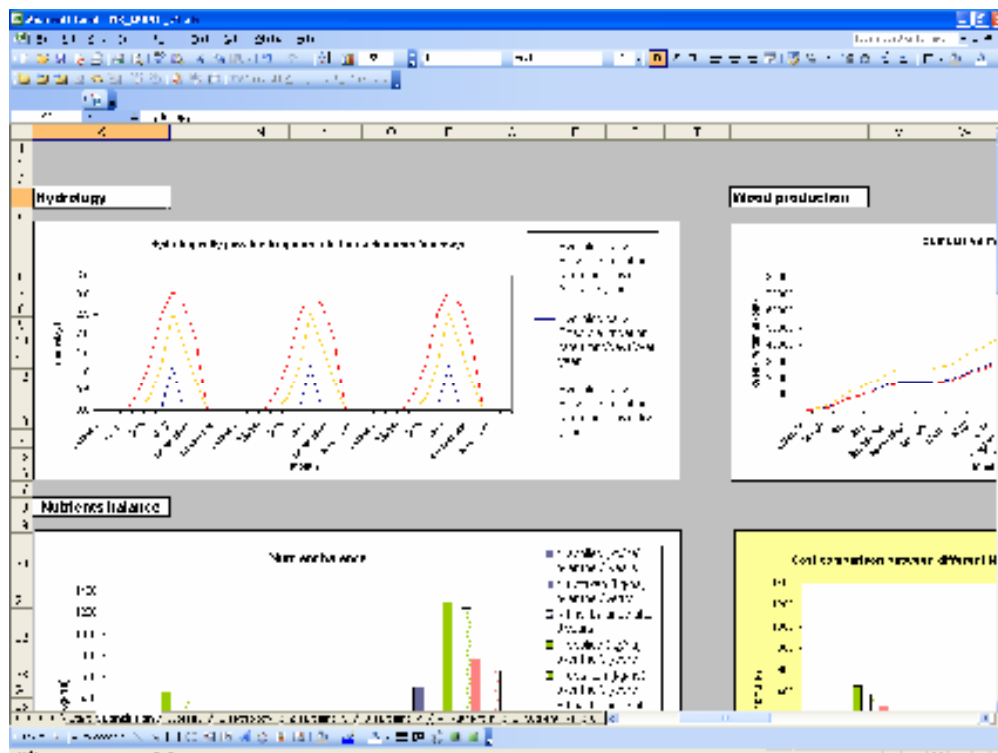


	Area to be cultivated (ha)	Volume of effluent (m³)	Plantation surface necessary to capture 90% of effluent (ha)	Volume of effluent (m³)	Volume of effluent (m³)	Total Area (ha)	Plantation surface necessary to capture 90% of effluent (ha)
Wet year	1.1	10	0.7	10	10	1.8	0
Average	1.1	10	0.7	10	10	1.8	14
Dry year	1.1	10	0.7	10	10	1.8	0

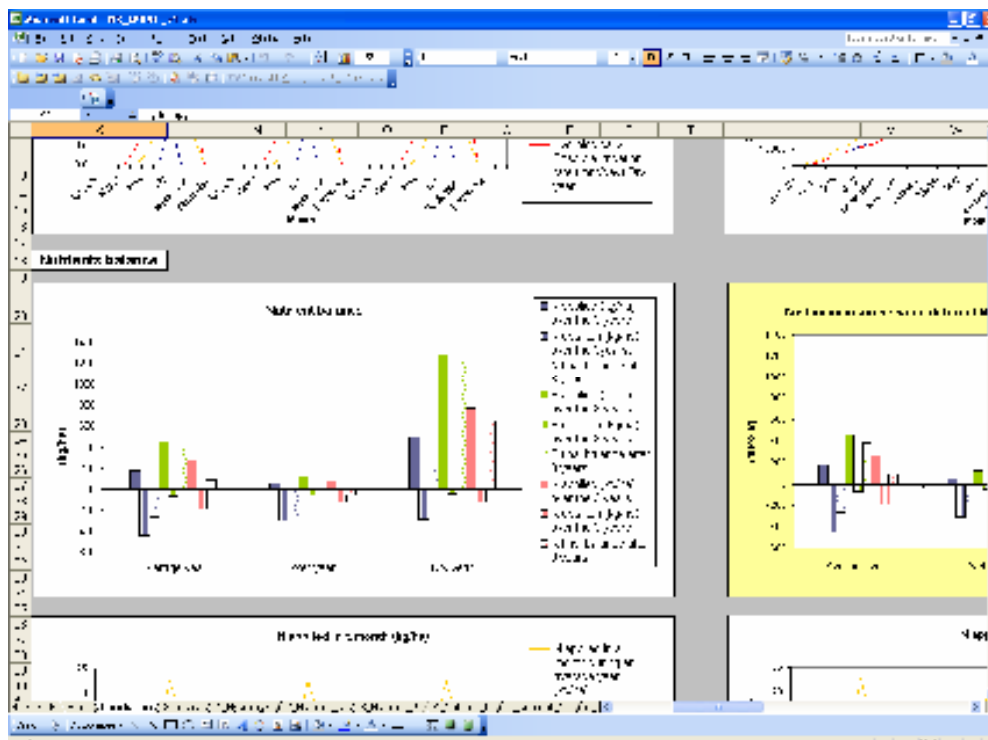
5.2 RESULTS FIGURES

Figures are regrouped in 3 groups:

Hydrology with the evolution of possible irrigation rate to maintain soil moisture to field capacity and comply NVZ regulations in (mm/day). Then, a second figure presents the evolution of the mass of wood produced over the 3 years in oven dry tons (odt).



Then, 2 graphs synthesising nutrient balance and nutrients removal costs in comparison with conventional biological nutrient removal (BNR) and chemical nutrient removal (CNR) in sewage treatment works.



And finally, nutrient application evolution graphs for N, P and K over 3 years.



5.3 7_ANNEXE WORKSHEET

All the constants are stored in this worksheet.

5.4 GLOSSARY WORKSHEET

A very basic glossary is available in this worksheet.

<http://www.landis.org.uk/gateway/reports/>

6. LAYMAN GUIDE

The main risks associated with the use of sewage treated effluent for irrigation are double; because of their composition in nutrients, especially N and P; subsequent leachate could conduct to eutrophication risks and because of their sodium content Na and electrical conductivity to soil degradation by superficial salinisation.

This model focuses on the reuse of partially treated effluent hence heavy metals and pathogens contamination issues are not taken in account as considered as not a significant threat with treated effluent use.

The model is constructed in a linear way to calculate the minimum area to be cultivated to treat the totality of wastewater produced at a specific sewage treatment work. The linearity of the model is materialised by the interdependence of worksheets constituting the model itself. Thus, first soil hydrological conditions will be used to calculate the maximum amount of wastewater applicable by month and by superficies' unit to maintain soil moisture under or as a maximum to field capacity. On maintaining soil moisture as a maximum to field capacity, vertical drainage of soil water to ground water is limited and potential nutrient leaching also limited at the same time. Thus, a hydrologically possible effluent application rate (mm/ha) is defined by the hydrological conditions.

Then, consequent nutrient application associated with wastewater application is looked at for each nutrient separately. A special emphasis is put on nitrogen, N, and phosphorus, P, as they are the potentially eutrophic nutrients and then, on sodium, Na, as it has a great impact on soil health itself.

The main restriction on nutrient application is regulated by nitrate application define in the DEFRA document RB 209 and restricted by nitrate vulnerable zone (NVZ) regulations if the site is located effectively in an NVZ. For this reason, with the hydrologically possible effluent application rate (mm/ha), an N application rate (kgN/ha.month) is calculated with effluent composition and compared and adjusted to meet regulations.

Then, once an N revised effluent application rate is calculated, as daily total volume of effluent production is defined, a minimum area of cultivation and additional storage for non applicable effluent are defined and consequently, because effluent composition is known, accordingly, P, K and Na application rates in kg-Nutrient/ha are then defined.

Thus, after N, P application is looked at specifically.

The WR_model does two different things:

- 3) It calculates the minimum area necessary to cultivate as a WaterRenew system and pond capacity to treat the totality of wastewater produced at a sewage treatment work on a specific site under specific meteorological and edaphic conditions.
- 4) It calculates the cost of installing the WaterRenew system and pond characterised in 1) and compares it to the cost of treating the same volume of wastewater with conventional nutrient removal methods (chemically or biologically).

The minimum area is calculated on taking in account nutrients regulation (RB209 recommendations). It also calculates additional storage for wastewater that cannot be applied either because of hydrological reason (soil moisture exceeding field capacity, and hence, any additional application would lead to drainage) or because of nutrient application limit regulation (especially on Nitrogen).

The model does not assess soil water composition during fertilisation and cannot be used to forecast soil real leaching events.

7. REFERENCES

- Allen, R. G. (R. G.). and Food and Agriculture Organization of the United Nations. (1998.), *Crop evapotranspiration : guidelines for computing crop water requirements*, Food and Agriculture Organization of the United Nations, Rome.
- Aronsson, P. G., Bergstrom, L. F. and Elowson, S. N. E. (2000/2), "Long-term influence of intensively cultured short-rotation Willow Coppice on nitrogen concentrations in groundwater", *Journal of Environmental Management*, vol. 58, no. 2, pp. 135-145.
- Great Britain. Dept. for Environment, Food & Rural Affairs (2002.), *Growing short rotation coppice : best practice guidelines for applicants to DEFRA's energy crops scheme*. DEFRA, London.

- GB, Parliament. Joint Committee on Statutory Instruments. (2008), *Action Programme for Nitrate Vulnerable Zones (England and Wales) Regulations 2008*. Great Britain. Parliament. House of Commons.; Great Britain. Parliament. House of Lords. (draft for consultation), The Stationery Office.
- Jones, R.J.A. and Thomasson, A.J. (1985). An agroclimatic databank for England and Wales. Soil Survey Technical Monograph No.16, Harpenden, UK. 45 pp.
- Myers, B. J., Bond, W. J., Benyon, R. G., Falkiner, R. A., Polglase, P. J., Smith, P. J., Snow, V. O. and Theiveyanathan, S. (1999), " Sustainable Effluent-Irrigated Plantations: An Australian Guideline", *CSIRO Forestry and Forest Products*, .
- Paranychanakis, N. V., Angelakis, A. N., Leverenz, H. and Tchobanoglous, G. (2006), "Treatment of Wastewater With Slow Rate Systems: A Review of Treatment Processes and Plant Functions", in *Critical Reviews in Environmental Science and Technology*. Boca Raton: 2006. Vol. 36, Iss. 3 and pg. 187, 73 pgs (eds.) , pp. 187-260.
- RAGG, J.M., JONES, R.J.A. and PROCTOR, M.E. (1988). The refinement and representation of spatial data in an information system using statistical and DBMS procedures, and trend surface analysis. *Geologisches Jahrbuch*. A104, 295-308. Hannover
- Rosenqvist, H. and Dawson, M. (2005), "Economics of using wastewater irrigation of willow in Northern Ireland", *Biomass and Bioenergy*, vol. 29, no. 2, pp. 83-92.

CHAPTER 10 : CONCLUSIONS AND RECOMMENDATIONS

1. GENERAL CONCLUSIONS

The aim of this thesis was to contribute to the further understanding of WaterRenew systems. Integrated knowledge of the hydrology, tree response and soil processes were considered necessary to inform estimates of the required minimum size for sustainable exploitation. This minimum size will optimise both efficient nutrients removal from wastewater and yield for short rotation coppice (SRC). In other words, the objective is to maximise the amount of nutrients that can be safely applied to land.

The conclusions from a literature review covering the risk and benefits of such systems (Chapter 2) identified the actual knowledge of the processes involved in those systems (soil N, P and K cycles in particular). Indeed, nutrient dynamics and cycling in fertilised vegetated systems have been studied in depth previously. However, the starting point of most of these studies was to optimise the application of fertilisers to crops; i.e. with the perspective of minimising their application. Then, the starting point in a WaterRenew system is the opposite; nutrients are abundant and their application not limited.

Then, the literature review also identified the lack of integrated understanding of such systems. A WaterRenew system can indeed be looked at as a unit composed of three main compartments; soil, soil water and plant. The sustainability of such a system will be compromised if at least one of its compartments is changed irreversibly. The limits can be hydrological with constant runoff or drainage being induced. They can also be chemical if inadequate amounts of nutrients are removed from the effluent applied or if irreversible accumulation of nutrients in soil occurs. Finally, these limits can be physiological with the trees' health being irreversibly compromised. The quantification of those limits and the limiting factors of such systems are not known. There is no knowledge of how much wastewater can be applied on a specific location before observing nutrients leaching or, if leaching starts to happen, if the system can be recovered i.e. how irreversible the damages are. Or also what can be the optimum irrigation rate for a WaterRenew system? From the literature review, soil finite P sorption capacity was identified as a potential limiting factor for the sustainability of a WaterRenew system. This is because the amounts of P brought by irrigation in the effluent are greater than SRC requirements. Therefore, because P solubility is low

compared to its affinity for soil particles, the non-uptaken P will tend to adsorb onto soil particles or soil matrix rather than staying in solution. However this can take place only as long as the soil P sorption capacity is not filled. In the literature, there have been numerous attempts at understanding and modelling those P processes however without great success. There is also another problem raised from the literature concerning soil salinisation risk. Drainage has to be limited in a WaterRenew system in order to prevent nutrient leaching. But one way to limit salinisation of soil when irrigating with water presenting slight risk is to over irrigate and effectively induce leaching.

In order to answer these questions, a field trial was set up at the Cranfield University sewage treatment works where *Salix viminalis*, *Populus trichocarpa* and *Eucalyptus gunnii* trees were planted to be irrigated with secondary treated effluent and applied by an automated drip irrigation system set up to maintain soil moisture to field capacity. Thus, the irrigation system was designed to operate within its hydrological limit. Its implementation was described in details in Chapter 3.

The effect and evolution of the different compartments of this WaterRenew system were reported in the previous chapters.

Chapter 4 presented the tree response to wastewater irrigation and its conclusions were summed up in the following points:

- Irrigation increased yield significantly for the 3 tree species studied.
- In spite of high hydraulic loads, yields remained within the averages reported in the literature for willow and eucalyptus but for poplar, yields were lower than the literature average for the same species. Eucalyptus performed the best in terms of yield and wood density.
- There was no reduction in yield related to Na stress even though over 1.9 ton-Na.ha⁻¹, 1.5 ton-Na.ha⁻¹ 1.6 ton-Na.ha⁻¹ were applied during the experimentation on willows, poplar and eucalyptus respectively.
- Willow trees uptook the greatest amount of effluent (over 1.800 mm.year⁻¹). Although its water use efficiency (WUE) was low, this may be an advantage for WaterRenew systems.

- Willow received the greatest amount of nutrients; 1023 kg-N.ha⁻¹ and 134 kg-P.ha⁻¹ for willow, 834 kg-N.ha⁻¹ and 108 kg-P.ha⁻¹ for poplar and 946 kg-N.ha⁻¹ and 127 kg-P.ha⁻¹ for eucalyptus for the 2 years of irrigation.

Hence, for both yields and nutrients' uptake points of view, eucalyptus trees performed the best. And from a WaterRenew system perspective, eucalyptus performed the best as well as it corresponds to a balance between water use and nutrients uptake. But eucalyptus keeps its leaves year long. Leaves need to be dried before being considered to be eventually used as biofuel. Therefore, leaf mass corresponds to an additional mass that needs to be transported and dried inducing additional costs which could decrease economical benefit.

Chapter 5 presented the soil response to wastewater irrigation and its conclusions were summed up in the following points:

- The amounts of N applied by irrigation were low compared to the soil TN pool and irrigation and tree did not have significant effect on soil TN.
- The amounts of P applied by irrigation was expected to affect soil Olsen-P but instead of an accumulation there was a reduction of Olsen-P and no effect on TP pool.
- The amounts of K applied remained low compared to the soil TK pool and irrigation or trees did not have any significant effect on it.
- The presence of tree had a smaller impact on the different variables monitored than irrigation.
- The amounts of Na applied by irrigation were high compared to initial Na in soil. Irrigation had a significant effect on Na and consequently on SAR by increasing their values significantly.

Therefore, Cranfield site WaterRenew system did not reach its soil organic and inorganic limits to retain and transform nutrients. Therefore, this revealed, prior to soil water analysis, a great potential to remove N and P from effluent.

Chapter 6 presented the soil water and groundwater's responses to wastewater irrigation and its conclusions were summed up in the following points:

- Irrigation did not have a significant effect on soil water TN concentrations. WaterRenew system, and in particular the soil lowered efficiently TN concentrations from effluent because the tree TN uptakes did not play a significant part.

- There was no P detectable in soil water indicating effective P sorption in the soil.
- For the K story, irrigation increased significantly K concentrations in soil water and tree presence had the reverse effect than expected. There was a significant concentration of K in soil water from planted plots. K removal capacity lies in soil mainly.
- For the Na story, irrigation and tree presence significantly increased Na concentration in soil water. This is probably because trees uptook water from effluent but not Na, hence Na got concentrated and started leaching as higher concentrations were measured at 60 cm than at 30 cm.
- For groundwater, there was a significant increase of K concentrations in groundwater samples taken downstream of the field compared to upstream samples but no increases in N, P and Na concentrations.

Chapter 7 presented the balance of nutrients in the Cranfield WaterRenew system and its conclusions were summed up in the following points:

- On planted plots, tree uptake may have contributed to retain a significant proportion of the nutrients applied into the WaterRenew system.
- The proportions of nutrients lost by drainage remained low (especially for N and P) and prevented groundwater from pollution.
- The major proportion of N and P applied (>50 %) were unaccounted for and might have been fixed or incorporated to soil organic and inorganic nutrients pools. N might be immobilised into soil organic matter or volatilised and P would have been mainly adsorbed by soil P sorption capacity. But because of the large size of the soil nutrients pool and the associated errors in measurements, it was not possible to validate these nutrients balances.

Chapter 8 presented an independent experiment studying columns with Cranfield soil on which P solutions were applied at different concentrations and maintaining different water content. Its conclusions were summed up in the following points:

- The majority of P applied is adsorbed by the soil.
- It was possible to estimate a robust linear relationship between the amount of P applied and the subsequent accumulation of Olsen-P for Cranfield chalky clayey soil ($R^2=0.87$).

- Soil moisture is very important in controlling P leaching; water saturated conditions will induce more P leaching than unsaturated conditions. Therefore, from a field application point of view, water logging should be avoided even when soils are irrigated with low P solutions as P will start to leach.
- The Heckrath Olsen-P threshold of 60 mg.kg^{-1} did not apply to Cranfield chalky clayey soil; P leaching was initiated before the threshold was reached for saturated columns.
- It is difficult to model P dynamics with simple equations and more studies are required.

Chapter 9 presented WR_MODEL, a spreadsheet-based design tool developed to dimension a sustainable WaterRenew system on a specific site, with a specific effluent, and a specific tree species. It also assesses its financial viability compared to a wastewater tertiary treatment unit on a sewage treatment work to remove nutrients. WR_MODEL was designed to be used in the UK as default data on soil and climate are UK specific. Calculations are also constrained to comply with UK specific recommendations in terms of fertilisation. The model was verified on an independent but incomplete set of data and therefore could not be validated. The sensitivity analysis identified a great sensitivity of the model to climatic conditions and not so much to soil type.

At the beginning of this study, the following objectives were formulated in relationship with the field trial set up at Cranfield University sewage treatment work:

Knowledge oriented objective: Understanding and quantifying processes in nutrients removal in WR system and optimisation. This objective can be subdivided in other objectives:

- **Objective 1) to improve wastewater treatment process understanding by soil and plant and quantify the relative importance of each compartment.**
- For N, P and K, the amounts applied were very small compared to their pool in soil. For P, WaterRenew system removal capacity was of 100 % as there was no P detectable in soil water even under unplanted plots and the amount of P uptaken by trees were less than the amounts applied. Therefore, soil P sorption capacity was efficient and was not challenged by the amount added. For N and K, they were measured in soil water however their concentrations were not significantly higher than in non-irrigated soil water samples. For N, they were even lower under planted

plots. Therefore again, WaterRenew system removal capacity was satisfactory and probably close to 80 %. In mass terms, the proportion of N leached represented less than 20 % of the total amount applied. As trees did not lower significantly nutrients contents in soil or soil water for any of the nutrients, and considering the amounts trees were able to uptake compare to N, P and K pools in soil, soil was probably responsible for these additional effluent nutrient removals.

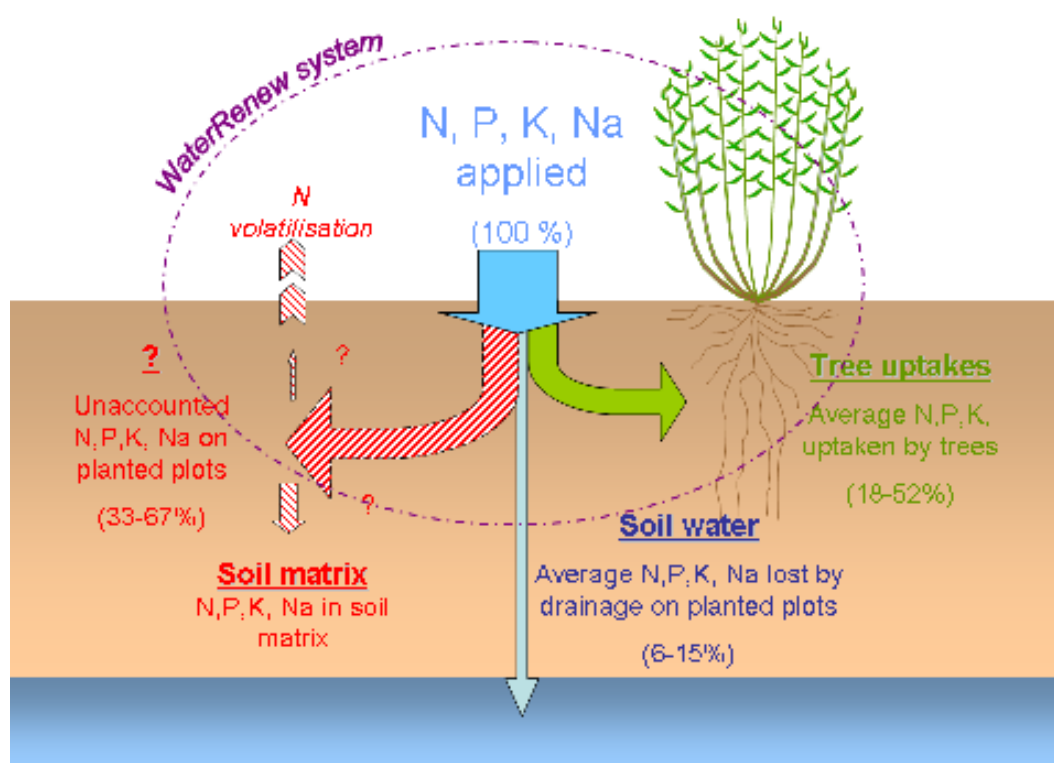


Figure 1 Nutrients fate and compartments of a WaterRenew system, summary.

- **Objective 2) to describe the temporal dynamics of P and N with an emphasis on P processes as they are time-dependent and have been less studied and understood.**
- In the literature, it was not recommended to fertilise with N during the establishment year. Indeed, it is usually expected to observe an important mineralisation of N when a site soil is disrupted. Cranfield site was irrigated during Year 1 and despite significantly higher mineral N content in soil during the first year, there was no significant effect of irrigation on N soil water concentrations.

- As the Cranfield site was exploited for two seasons, it was expected that seasonal effects on soil and soil water chemistry would be identified and validated. However, none were identified for soil and soil water. There was a seasonal pattern for the irrigable amounts of effluent as they were closely related to tree water uptake, which in turn depended on tree growth. Hence, the amount of effluent applied was not constant during the year, and therefore, with these irrigation settings, it was not possible to verify whether there was a seasonal effect on the soil capacity to retain and transform nutrients.
- Hence, with the irrigation settings of the WaterRenew system on Cranfield site, this maintained soil moisture to field capacity. This means that the system was run effectively at its hydrological limits; it was not pushed to its chemical limit. In other words, it was not possible to induce by irrigation N, P or K leaching in soil water. There was an attempt to push the system hydrologically through higher effluent application rates until there was an increased risk of surface runoff and ponding. This was also the physiological limit as tree health was adversely affected.
- P was expected to accumulate in soil by soil P sorption capacity until a point it will eventually start leaching. However, no P could be measured in soil water. Therefore, it was not possible to quantify any temporal dynamics for P leaching processes. For this reason, a separate laboratory soil column experiment, with Cranfield soil, was set up in order to find Cranfield soil P sorption capacity limit. However, this column experiment failed to bring a clear understanding on soil P sorption capacity filling processes. It was proven again that arbitrary threshold as Heckrath 60 mg.kg^{-1} of soil of Olsen-P underestimated the amount of P applicable before observing any leaching. But the leaching patterns observed could not be fitted to a simple model (linear, polynomial, and exponential).

Practical tool development objective: Development of a model to assess feasibility and sustainability. This objective can be subdivided in other objectives:

- **Objective 1) Development of a model as a useful process for conceptualisation of this environmental system.**
- WR_model was developed. Climate and soil physical properties were identified as the most important factors influencing the size of a WaterRenew system for a specific site. A WaterRenew system is also a forestry system as SRC are grown on it. Therefore, effluent irrigation rate has to be limited in order to maintain soil in well

watered conditions for trees to grow and general irrigation recommendations have to be followed. Cranfield field trial results revealed that the amount of nutrients irrigable then are very low compared to soil nutrients pools expect for Na.

- This reduces WaterRenew system utilisation to small to very small scale sewage treatment plant. Indeed, England and Wales' annual average soil moisture deficit (SMD or amount irrigable to bring soil moisture back to field capacity) range between 75 mm.month^{-1} to over $250 \text{ mm.month}^{-1}$. These SMD correspond to $75,000 \text{ L.ha}^{-1}.\text{month}^{-1}$ to over $250,000 \text{ L.ha}^{-1}.\text{month}^{-1}$. As UK household average water consumption is $150 \text{ L.day}^{-1} \cdot \text{person}^{-1}$ and making the assumption that the totality of the water consumed needs to be treated, these SMD would correspond to 17 to 55 population.equivalent.ha⁻¹ for an annual average. As the UK average production woodland area size was reported in 2005 equal to 100 ha (Tilhill et al, 2005), this technology would be limited for a range of 1,700 to 5,000 p.e. and would be difficult to implement at a large scale.
- **Objective 2) Recommendation for design and operation of field system: how big does a WaterRenew system need to be?**
- WR_model can give the answer for a specific site if effluent characteristics (quantity, quality), soil properties and climate data are available. However, WR_model relies heavily on Cranfield field trial data and therefore, its utilisation should remain only qualitative if the location soil is very different from a clay.

2. CRITICAL ASSESSMENT OF ACHIEVEMENT

First of all, the Cranfield field trial gave reassurance in the feasibility of a WaterRenew system as it succeeded in removing efficiently nutrients from a secondary treated effluent applied under the worst case scenario: a slow permeable clayey soil, a shallow water table and wet year conditions.

The Cranfield field trial was run from July 2006 to February 2008. Hence, its results reflect only short term processes. Therefore, the long term effects of implementing a WaterRenew system are only speculative. Indeed, the scope of this research did not provide sufficient information for the validation of either the nature or the upper limits of the WaterRenew system's limiting factors.

The P leaching column experiment demonstrated the importance of P sorption capacity within clay soils and how if well managed, by avoiding water logging, high amounts of P can be applied with a limited risk of leaching.

The results are relevant only for a chalky clayey soil and as there were no comparative experiments conducted with different soils, the extrapolation of these results to other locations should be applied carefully.

Cranfield site is a field trial, so by definition its size is small (0.048 ha) therefore it is difficult to forecast how good the findings on this field trial can be up scaled.

This trial was hydrologically driven because soil moisture content was expected to impact greatly both soil capacity to retain and transform nutrients and tree health. But the trial could have been nutrients driven with the amount of effluent calculated according to target amounts of nutrient to be applied rather than the volume of effluent because N application is the only parameter regulated (cf. NVZ). Although soil moisture was maintained the same on all plots, the amounts of effluent applied on the different covered plots were not the same. Therefore, the amounts of nutrients applied on them were different. This can then question how comparable the different plots are as they did not receive the same amount of effluent and nutrients and in particular how comparable their behaviours to irrigation are. However, this field trial demonstrated how NVZ requirements might be over protective. If the effluent application would have been nutrients driven, it is unlikely that such N targets would have been considered, especially with Cranfield classified as NVZ. More than 510 kg-N.ha^{-1} was effectively applied in average per year on willow planted plots, hence, almost twice the maximum amount authorised on an NVZ (250 kg-N.ha^{-1} per year) but there was no significant increase in TON concentrations in soil water.

For the effect of a WaterRenew system on trees, in the Cranfield trial, there was no clean water irrigation; therefore, it was not possible to quantify separately nutrient effect from water effect. On the other hand, this field trial demonstrated the significant potential of *E. gunnii* as SRC in the UK as it performed better indeed than *P. trichocarpa*, a native species even under very wet conditions.

Thus, this trial succeeded in demonstrating the great ability of a WaterRenew system on a clayey soil, to retrain and transform nutrients applied within a secondary treated effluent. This ability was greater than expected as the system's hydrological and physiological limits were reached before it was possible to observe nutrients leaching

in soil water. Indeed for WaterRenew systems lying on clay or slowly permeable soils, the hydrological limit appeared to be the limiting factor; infiltration rate and soil field capacity dictated the irrigation rate, the time when irrigation was possible (cf. winter application) and tree health as they have a direct effect on how well trees were rooted. Once again, these results are for slowly permeable soils only because on more permeable soils, soil capacity to retain and transform nutrients might be challenged. As more volume of effluent will pass through the soil, more nutrients would have to be treated.

3. RECOMMENDATIONS FOR FUTURE RESEARCH

The Cranfield field trial was run from July 2006 to February 2008. Hence, its results reflect only short term processes. A long term monitoring of such trials would be beneficial. Moreover, these results are only relevant for heavy soil and similar trials on very different type of soil would add confidence in these systems.

The laboratory soil column P leaching experiment focused only on Cranfield chalky clayey soil under only 2 soil moisture contents, saturated and constant or very variable. It also failed to provide a simple model for P sorption dynamics in soil. Therefore, studies with lighter soil and under more different moisture content would help modelling P sorption processes.

On the nutrients balance point of view, in this work, no gaseous loss was measured at all. They were assumed to be negligible because soil moisture was kept under or at field capacity preventing or limiting anaerobic conditions in the superficial soil layer to happen. This needs to be verified by measurements. Utilisation of isotopes, ^{15}N and ^{32}P and ^{33}P would help to trace where the nutrients applied by wastewater irrigation really went.